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ReNu2Cycle

# Developing a methodology to determine sustainability of recycling derived fertiliser products

Version 1.0

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## Abstract

This report presents a novel methodology for assessing the sustainability of recycling-derived fertiliser products (RDF) in comparison to conventional fertilisers within the framework of the INTERREG VI B North-West Europe project ReNu2Cycle (project code NWE0100073). Developed specifically for RDF, the Sustainability Assessment for Fertilisers (SA-4F) introduces a transparent, multi-criteria approach to evaluate RDF in comparison to synthetic mineral fertilisers. The methodology applies 15 criteria across ecological, economic, and social dimensions and is grounded in sustainable economic principles and the UN Sustainable Development Goals (SDGs). Against the backdrop of rising fertiliser import dependency, supply chain disruptions, and the environmental burden of synthetic fertiliser use, this assessment addresses the urgent need for resilient, circular, and regional nutrient management strategies. By enabling a comprehensive sustainability comparison, the SA-4F methodology supports informed decision-making and fosters the transition toward more sustainable and regenerative agricultural systems in North-West Europe.

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# List of Abbreviations

%................Percent
$(NH_4)_2SO_4$..Ammonium Sulphate
$[NH_4]^+$........Ammonium
°C..............Degree Celsius
16S ...........16S ribosomal DNA
3CCI..........Three-Country Concentration of Imports
a................Willingness to pay/acceptance to pay
As..............Arsenic
C ................Carbon
CBAM ........Carbon Border Adjustment Mechanism
Cd ............. Cadmium
CE .............Circular Economy
$CH_4$ ...........Methane
$cm^3$ ...........Cubic centimetres
$CO_2$ ...........Carbon dioxide
$CO_2$eq........$CO_2$ equivalent
COVID-19..Coronavirus disease 2019
C-P ............Colonizer-Persister
Cr(VI) .........Chromium VI
EOL...........End-of-Life
ESNI..........European Sustainable Nutrient Initiative
EU .............European Union
GEMIS ....... Global Emission Model for Integrated Systems
GHG..........Greenhouse Gases
Hg.............Mercury
IFA ............International Fertiliser Association
ITS.............Internal Transcribed Spacer DNA
K................Potassium
$K_2SO_4$.........Potassium Sulphate
KCl ............Potassium Chloride, Potassium Sulphate
$KNO_3$ .........Potassium Nitrate
LCA ............Life Cycle Assessment
LF DIG .......Liquid Fraction of Digestate
LLA ...........Living lab approach
Mg ............Magnesium
mg/kg........Milligrams per kilogram
mt.............metric tonne

N ................ Nitrogen
$N_2O$ ........... Nitrous Oxide
NFI ............. Nematode Functional Index
$NH_4MgPO_46H_2O$ ........................................... Magnesium Ammonium Phosphate
Ni ............... Nickel
NWE .......... North-West Europe, North-West Europe
OTU ........... Operational taxonomic units
p................. Production costs
P................. Phosphorus
$P_2O_5$ ........... Triple Superphosphate
Pb .............. Lead
ppm........... Parts per million
PSM ........... Price Sensitivity Meter, Conventional fertiliser price
RDF............ Recycling Derived Fertilisers
SDG ........... Sustainable Development Goals
SWIFT ........ Society for Worldwide Interbank Financial Telecommunication
UN ............. United Nations
WCR........... Weighted conflict risk
WWTP ....... Wastewater treatment plants
x ................ Profit margin

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# 1 Introduction

## 1.1 Problem Outline

### 1.1.1 Sustainability assessment as part of project scope

The INTERREG VI B North-West Europe project "ReNu2Cycle: Recycling of Nutrients to Close the Fertiliser Cycle" (project code NWE0100073) provides the scientific framing to develop and apply a multi-criteria sustainability assessment of self-produced recycling derived fertilisers (RDF) in reference to synthetic mineral fertilisers in NWE. This methodology was developed specifically for the first time for RDF. The methodology under the ReNu2Cycle project scope is called 'Sustainability Assessment for Fertilisers' (SA-4F).

This report establishes the methodical framework for a multi-criteria sustainability assessment of self-produced RDF in NWE. The assessment is operationalized using 15 criteria spanning social, economic, and ecological dimensions. The (theoretical) foundations of this multi criteria assessment include the framework of sustainable economics, as well as the Sustainable Development Goals (SDG). The objective of this report is to develop a transparent and comparable methodology that can support decision-making for a transition toward a more sustainable agricultural system.

### 1.1.2 Challenges in current fertiliser supply

In modern agriculture, the use of synthetic fertilisers and intensive practices have made it possible to feed a growing global population, yet they come with serious environmental and health costs. The European Union (EU) . currently imports over six million tons of conventional mineral fertilisers annually, leading to supply dependencies for EU food security (EC DG AGRI 2019).

Recent challenges, such as the COVID-19 pandemic situation and the Russian invasion of Ukraine, have further underscored the importance of ensuring secure and stable fertiliser supply chains and a political shift for strengthening EU internal markets in the fertiliser production sector. Fertiliser prices hit record highs in spring 2022 after Russia, the largest exporter, invaded Ukraine, worsening an already strained supply due to COVID-19 disruptions. Russian fertiliser exports were hindered by sanctions, including the exclusion of Russian banks from SWIFT and insurers' reluctance to cover shipments in the war zone. Additionally, export routes through the EU were blocked (Broom

2023). This dependency on imported synthetic fertilisers disrupts regional and inter-regional circular bioeconomy value chains and leaves the EU dependent on external supplies and prices.

### 1.1.3 Limits of synthetic fertilisers

The widespread use of synthetic fertilisers, aimed at maximizing crop yields, has led to significant carbon dioxide ($CO_2$) emissions and environmental impacts, including soil degradation, water pollution, and ecosystem imbalances. Furthermore, the continuous application of synthetic fertilisers depletes soil health, stripping it of its biodiversity and leading to nutrient imbalances that can ultimately reduce productivity and resilience over time. Despite this, essential nutrients in NWE are frequently lost due to the persistence of a predominantly linear economic model. Organic resources from the waste sector (e.g., biowaste, manure, sewage sludge, and food scraps), which could otherwise be recycled, often remain underutilized. Similarly, nutrient surpluses in agricultural regions—characterized by excessive concentrations of nitrogen and phosphorus—are inadequately managed. This results in significant losses through runoff, emissions, and landfill deposition, contributing to environmental degradation and inefficiencies in nutrient cycling.

## 1.2 Research objective

### 1.2.1 Context of EU goals

To respond to challenges on food supply, the EU has already implemented a broad policy framework to protect food security and enable a circular economy (CE) in the EU while enhancing the resilience of the agricultural sector. In particular, the Farm to Fork Strategy lies at the core of the European Green Deal, with the goal of transforming food systems to be fairer, healthier, and more environmentally sustainable. Additionally, the CE policy framework of the EU represents a paradigm shift toward sustainable resource management by promoting the reduction, reuse, and recycling of materials. A transition to a more robust CE framework to guarantee food supply and reduce environmental impacts requires targeted interventions to address these challenges.

This shall be encouraged via cross-border production and trade of RDF for the functioning of the European single-market (TFEU: Art. 3+4), with additional initiatives to promote sustainable farming practices and build capacity for a sustainable fertiliser market in NWE.

### 1.2.2 Role of RDF

In response, innovative RDF present a promising path to more sustainable and independent EU agriculture. By processing these organic materials, high-quality nutrient products containing nitrogen, phosphorus, and potassium are created. Production of RDF involves advanced technologies like composting, anaerobic digestion, thermochemical processes, and other innovative methods, all of which help transform organic waste into safe, usable forms while reducing waste and greenhouse gas (GHG) emissions. The resulting recycling fertilisers can then be distributed regionally, reducing reliance on synthetic fertilisers and fostering closed nutrient cycles. However, challenges such as pollutant control, activating EU supply-demand chains for availability and acceptance still remain.

### 1.2.3 Sustainability assessment

To understand the advantages and potential of RDF compared to synthetic fertilisers, it is essential to conduct a comprehensive sustainability assessment. Such assessments help in evaluating the full range of environmental, economic, and social impacts associated with RDF use. By comparing these impacts to those of synthetic fertilisers, stakeholders can make informed decisions regarding the sustainability of RDF in modern agriculture. This evaluation is crucial to advancing agricultural practices that not only meet global food security needs but do so in a way that conserves and regenerates essential natural resources and establish a social-wealth based CE for future generations. This report serves as a methodological foundation and a guide for the implementation of the assessment.

## 1.3 Methodology report

### 1.3.1 Structure

The following section outlines the development of the assessment framework, followed by a detailed overview of the 15 sustainability criteria, their indicators, and their operationalisation. This methodology report serves as a reference guide for operationalizing and evaluating each criterion. It can be used throughout the assessment process and for reviewing specific details to better understand and verify completed assessments.

### 1.3.2 Criteria development

The criteria and indicators for the SA-4F were developed through a collaborative co-design process with expert discussion within the project's research consortium. It involved specialists from different disciplines to share their knowledge. These discussions were organised across the three sustainability dimensions: environmental, socio-cultural, and economic. Participants were invited to bilateral meetings with the project team responsible for the SA-4F. Throughout the series of expert talks and literature studies, the professionals explored the challenges involved, how they relate to the target system, and which indicators would be most suitable for measuring them.

### 1.3.3 Report series

This report is the first in a five-part series. After this introduction to the general methodological framework and indicator development, the following three reports will separately assess the five sustainability criteria for each dimension: social (D.1.2.2), economic (D.1.2.3), and environmental (D.1.2.4). The fifth concluding report (D.1.2.5) will provide a comprehensive analysis of the overall sustainability of RDF products, identifying strengths and opportunities and giving an in-depth overview of the sustainability of each RDF product. Visualisations and Factsheets (D.1.4.3) aligned for project specific target groups (as e.g., RDF user/farmers, policy decision-makers, resource and technology providers, market sale players) will portray the outcomes of the multi-criteria sustainability assessments of self-produced RDF in NWE. By providing clear, stakeholder groups targeted visualizations and explanatory texts, the project aims to make the sustainability impacts of RDF more accessible to stakeholders in NWE.

# 2 Development of Sustainability Assessment Framework

## 2.1 SDG Assessment as Global Target System

Sustainability has been recognized as an overarching and global social development goal of the United Nations (UN) since the Rio Conference in 1992. Along this line, in 2015, the UN General Assembly adopted the 2030 Agenda for Sustainable Development which comprises of 17 SDG (see Figure 1: 17 Sustainable Development Goals (UNRIC 2024)). Each goal typically has eight to 12 targets, and each target has between one and four indicators used to measure progress toward reaching the targets. This results into a total of 169 specific sub-targets and more than 230 indicators with a target completion date, as the name of agenda suggests, of 2030. The SDG are influenced by the earlier Millennium Development Goals, yet unlike them, which primarily focused on developing nations, SDG are universal in nature and applying to all countries of the world. This is establishing SDG as a transformative approach to global development. They embody a collective commitment to achieve sustainable development across the three fundamental and interconnected dimensions of sustainability. The dimensions are

- Ecological Dimension (planet, SDG 6, 12-15): Focuses on environmental sustainability, encompassing challenges related to resource conservation, pollution reduction, biodiversity protection, climate change mitigation, and sustainable land use.
- Economic Dimension (prosperity, SDG 7-11): Addresses economic sustainability by examining challenges related to economic growth, job creation, equitable resource distribution, and financial stability.
- Social Dimension (people, SDG 1-5): Considers social sustainability, including challenges tied to community well-being, cultural preservation, social equity, and public health.

Additionally, SDG 16 and 17 highlight the importance of peace and partnerships.


Figure 1: 17 Sustainable Development Goals (UNRIC 2024)

The UN SDG mark for a universal and transformative development strategy that aim to commit the global community to achieving sustainable development across economic, social, and environmental dimensions in a cohesive and integrated approach.

While in several SDG the sustainability of activities in the agri-food sector (i.e., agriculture, livestock and agri-food industry) is included, with regard to ReNu2Cycle the SDG 2, Zero Hunger, serves an anchor goal (bottom line) of the analysis. The goal addresses the need to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture by 2030. This highlights the importance of addressing hunger and food insecurity as foundational issues that impact health, education, and economic development. The International Fertiliser Association (IFA) understands these goals as a vital framework for promoting the sustainable production of fertilisers.

Meeting the SDG can be monitored by selected indicators. For instance, the UN SDG Indicator database lists 231 SDG indicators for countries, areas or regions (UN Stats 2024). Within the EU Eurostat monitors the EU's progress towards the SDG using a set of 102 indicators (EC und Eurostat 2024). Nevertheless, the SDG indicator set lacks specific indicators on economic aspects regarding market, prices, effects on trade balances etc (Gapp-Schmeling 2020; Rogall und Gapp-Schmeling 2021). For that reason and because of very viable experiences of using similar approaches for a sustainability assessment in other projects the project team decided to develop an indicator framework based on the theory of sustainable economics.

## 2.2 Theory of Sustainable Economics bases as multi-criteria sustainability assessment within three dimensions

### 2.2.1 Global challenges within 3 dimensions

To develop a corresponding framework that allows operationalising sustainability goals one can build on the previous work of the Sustainable Economics Network, which was founded in 2009 (today over 300 members, including 200 lecturers and scientists). On the basis of the work on several monographs (Rogall 2008; 2004; 2002; 2000), Sustainability experts from Europe formed the Network of Sustainable Economics. The founding members agreed on ten core statements as guiding principles for their work. The eighth key statement calls for a goal and indicators system measuring sustainability. Therefore, the members of the network have developed such a system (Gapp-Schmeling 2022; Rogall und Gapp-Schmeling 2021).

As a starting point for the goal and target system Sustainable Economics summarises the global problems and megatrends of the 21st century in a model-like manner in the three sustainability dimensions (ecological, economic and socio-cultural dimensions), each with five problem areas. The goal and target system thereby includes the environmental goals of the EU (TFEU: Art. 191), the economic goals of the German Stability and Growth Act of 1967 (which are also reflected in the EU) as well as specific social goals.

The challenges are summarised in Table 1 below.

*Table 1: Global challenges within the three dimensions of sustainability*

| No. | Ecological | No. | Economic | No. | Social-cultural |
|---|---|---|---|---|---|
| 1) | Global warming | 6) | Negative developments on the labour market | 11) | Erroneous trends in the economy, politics, society |
| 2) | Destruction of biodiversity and landscape diversity | 7) | Insufficient satisfaction of basic needs | 12) | Social insecurity, poverty, demographic change |

| | | | | | |
|---|---|---|---|---|---|
| 3) | Consumption of non-renewable resources | 8) | Instability of monetary value and financial markets, concentration, externalities. | 13) | Inequality of opportunities, unequal distribution of income and wealth |
| 4) | Overuse of renewable resources | 9) | Imbalances in global trade, dependencies, underdevelopment. | 14) | Internal and external insecurity, violent conflicts. |
| 5) | Hazard to human health from pollutants. | 10) | Public debt, inadequate endowment of merit goods. | 15) | Technological risks (e.g., genetic and nuclear engineering, automation) |

*Reference: Own table*

The target system can be adapted for various applications and is considered suitable for assessing the degree of sustainability of economies, political strategies and technological options and was used, among other projects, in the German research project “KoWa – Wärmewende in der kommunalen Energieversorgung” (German funding reference number 03EN3007; funded by the German Federal Ministry for Economic Affairs and Climate Action) implemented comprehensively. This target system applied and modified to the subject of RDF Assessment.

## 2.3 Developing a target system for sustainable RDF

### 2.3.1 Theoretical basis

Sustainability is often framed through mission statements or broad objectives. Any empirical analysis on sustainability of RDF therefore requires the establishment of specific and measurable indicators and target values what sustainability in the given context entails.

Within ReNu2Cycle, operationalising measurable indicators for RDF requires an understanding that sustainable economics is grounded in two fundamental paradigms (Gapp-Schmeling 2020):

1. All economic activities must adhere to given ethical principles.

2. All economic actors—including consumers, companies, and the state—must actively participate in addressing and solving the central 15 sustainability challenges of the 21st century as organised by the SDG.

Economic theories are applied in research to understand and forecast economic development. Some theories set the frameworks for the way businesses run today, yet they (often) fail as they are not sustainable for society in the long run. Sustainability in this project context is understood as a form of economy and society that is lasting and can be lived on a global scale. The Theory of Sustainable Economics integrates sustainability research findings into regional economies, applying ethical principles and sustainable development criteria to market activities. Sustainable economic practices are defined as those that achieve adequate ecological, economic, and social-cultural standards for current and future generations while respecting the earth's “planetary boundaries” (Rockström et al. 2009). This embodies the principles of intra- and intergenerational justice (Rogall 2000). Intragenerational justice asserts that no individual, community, or nation should consume more resources than others. Meanwhile, intergenerational justice emphasizes equitable distribution of resources, ensuring that future generations can make their own choices regarding production and consumption. Similar, the Sustainable Economics Network emphasises sustainable economics as an economic theory that is rooted in transdisciplinary principles (Polanyi 1944/2019; WBGU 2011). Recent research urged social scientists to broaden the scope beyond that of “safe planetary targets” (Gupta et al. 2021). Safe targets are defined as biophysical thresholds that must not be surpassed to avoid the collapse of the Earth system with the 1,5°C goal being the most prominent one with regard to climate change. Not meeting these targets may have detrimental effects on human well-being. This is why targets must be integrated within these boundaries to account for “planetary justice” (Rockström et al. 2021), while considering the interdependencies and trade-offs between environmental and social objectives. Safe planetary targets can help mitigate harm and enhance human well-being by contributing to access not only to food but also to water and energy (Gupta et al. 2021).

### 2.3.2 Alignment with SDG

Each target of the goal and target system of Sustainable Economics can primarily be aligned with one or more UN SDG, which is advantageous, as countries, regional authorities, and companies are encouraged by the SDG to regularly document their sustainability contributions. In the following criteria description, the specific SDG relevant to each objective are identified. The sustainability assessment conducted in ReNu2Cycle thereby enables the demonstration of each RDF solution's contribution to the SDG.

### 2.3.3 Target-system Sustainable Economics

From the perspective of Sustainable Economics, the 15 challenges were the starting point (see Table 1) to develop goals and indicators. As mentioned above the goal and target system reflects on the three dimensions of sustainability (ecological, economic, and socio-cultural), each encompassing five key problem areas. Moreover, it includes goals from the political agenda of the EU.

It is essential to translate the abstract global challenges and related target system under the three dimensions into actionable and measurable indicators to assess the suitability performances. To measure the level of sustainability of an economy, product or project, it is not feasible to collect and evaluate an unlimited amount of information and data. Therefore, we need a measurement system that simplifies complexity but accurately represents it. To maintain clarity, people must focus on a selected number of particularly meaningful trends, which can then serve as indicators for societal development in key areas of concern. The selection of such a metric, which represents multiple developments, is referred to as an indicator. (Rogall & Gapp-Schmeling, 2021). At over 200, the number of UN SDG indicators is so high that a comparison becomes nearly impossible. Moreover, not all indicators have sufficiently quantified and time-bound action goals, making an actual assessment impossible in these cases. To assess the degree of goal achievement, indicators that are also used for the SDG can largely be applied.

A large proportion of the goals can be allocated to one or more UN SDG. However, a detailed comparison reveals that suitable SDG indicators are lacking for important quality goals. The goal and indicator system of the Sustainable Economics is supportive here, not intended as a final concept, but rather as a foundation for discussion.

For assessing the sustainability of fertilisers, the objectives and indicators need to be adapted. Table 2 translates the global challenges into goals. With the focus on assessing RDF, it seems more important to distinguish different goals regarding nature compatibility than to distinguish between renewable and non-renewable resources. Therefore, the target system has been slightly adapted.

*Table 2: Target-system of the challenges (criterion) across the three dimensions of sustainability in the context of fertiliser use*

| | Challenges | Global goal | Quality goal for fertilisers |
|---|---|---|---|
| No. | Ecological | | |
| 1) | Global warming | Limitation of climate change regarding the Paris goals | Low GHGE in producing and using RDF |
| 2) | Destruction of biodiversity and landscape diversity | Nature compatibility: Preservation of the diversity of species and landscapes | Nature compatibility: Preservation of the diversity of Mesofauna species in Soils |
| 3) | | | Preservation of the diversity of Microbial Taxa in Soils |
| 4) | Consumption of non-renewable resources | Steady reduction in Sustainable use of renewable resources (regeneration rate) | Nutrient Input vs. Output Ratio |
| 5) | Hazard to human health from pollutants. | Healthy living conditions | Heavy Metal Compliance Index |
| No. | Economic | | |
| 6) | Negative developments on the labour market | Decent work: secure jobs, no vulnerable employment | Contribution to (inter)-regional added value |
| 7) | Insufficient satisfaction of basic needs | Satisfaction of basic needs: with sustainable products | Market availability |
| 8) | Instability of monetary value and financial markets, concentration, externalities. | Stability of monetary value and financial markets, appropriate concentration, low externalities | Cost stability |

| | | | |
|---|---|---|---|
| 9) | Imbalances in global trade, dependencies, underdevelopment. | Foreign trade balance, high level of self-sufficiency, reduction of dependencies | Low external (economic) dependency |
| 10) | Public debt, inadequate endowment of merit goods. | State budgets that are capable of financing good equipment with merit goods | Financial Planning Stability |
| No. | Social-cultural | | |
| 11) | Erroneous trends in the economy, politics, society | Establish good governance | Establish good governance for acceptance and awareness for RDF uptake |
| 12) | Social insecurity, poverty, demographic change | Avoidance of poverty and dependencies | Low dependencies |
| 13) | Inequality of opportunities, unequal distribution of income and wealth | Equal opportunities uptake | Democratic and decentralized supply chain |
| 14) | Internal and external insecurity, violent conflicts. | Geostrategic independency (EU) | Low conflict potential |
| 15) | Technological risks (e.g., genetic and nuclear engineering, automation) | Abandonment of technologies with significant risks | Low technological risk |

*Reference: Own table*

## 2.4 Operationalising measurable indicators

The Theory of Sustainable Economics is applied and adapted for the multi-criteria sustainability assessment of self-produced RDF in NWE and makes on top contributions to the designated SDG goals. This methodology was adopted specifically for RDF. This methodology has already been applied in other projects, such as the German research project "KoWa – Wärmewende in der kommunalen Energieversorgung" (German funding reference number 03EN3007; funded by the German Federal Ministry for Economic Affairs and Climate Action). In the KoWa project, a comprehensive sustainability assessment of various heat supply concepts was conducted. The KoWa goal was to analyse and evaluate technical, economic, legal, and socio-cultural requirements to develop highly integrated municipal heat supply concepts. The assessment followed a multi-criteria approach, considering various indicators and criteria to holistically capture the sustainability of the respective supply concepts.

The criteria and indicators for the individual quality have been aligned and adapted for use in the ReNu2Cycle research project. The overarching quality target from Table 2 has been taken into account. The criteria and indicators for the SA-4F were developed collaboratively within the project's research consortium through expert discussions. Specialists shared insights across three sustainability dimensions—environmental, socio-cultural, and economic—in bilateral meetings with the SA-4F project team. Through these discussions and literature reviews, the team identified suitable indicators for each target. For each dimension, the criterion (goal to respond to global challenge) and the related target and indicator was deemed crucial for capturing the most meaningful and measurable (quantitative) or descriptive (qualitative) impacts.

Table 3 presents the results of the joint decision-making process to develop a multi-criteria sustainability assessment methodology for self-produced RDF in NWE. The next chapters describe the derivations of the chosen criteria, SDG intersections and indicators per dimension.

*Table 3: Target-system of the challenges within the three dimensions of sustainability and their indicators in the context of RDF sustainability*

| Overarching (anchor) goal: SDG 02 Zero Hunger | | |
|---|---|---|
| Ecological Dimension | | |
| Criterion (target system goal to respond to global challenge) | Focus SDG | Criterion/ Indicator |
| Limitation of climate change regarding the Paris goals | SDG 13: Climate Action | Green House Gas Emissions $CO_2$ equivalent ($CO_2eq$) |
| Nature compatibility: Preservation of the diversity of Mesofauna species in Soils | SDG 15: Life on land | Soil biological degradation: loss of soil biodiversity- Classification scales of CP nematodes spectrum |
| Nature compatibility: Preservation of the diversity of Microbial Taxa in Soils | SDG 15: Life on land | Biodiversity of bacteria and fungi.<br>Abundance of nutrient cycling (N, P) genes |
| Sustainable use of soil as a non-renewable resource | SDG 12: Responsible consumption and production | Nutrient Input vs. Output Ratio |
| Healthy living conditions | SDG 3: Good health and well being | Heavy Metal Compliance Index |
| Economic Dimension | | |
| Criterion (target system goal to respond to global challenge) | Focus SDG | Criterion/ Indicator |
| Limitation of climate change regarding the Paris goals | SDG 13: Climate Action | Green House Gas Emissions CO2eq |
| Decent work: secure jobs, no vulnerable employment | SDG 08: Decent work and economic growth | Regional- and value added within the supply chains |
| Satisfaction of basic needs: with sustainable products | SDG 09: Industry, Innovation and Infrastructure | Availability & accessibility in terms of market penetration (perspective farmer) in regions |

| | | |
|---|---|---|
| Stability of monetary value and financial markets, appropriate concentration, low externalities | SDG 12: Responsible consumption and production | Appropriate prices for demand and supply |
| Foreign trade balance, high level of self-sufficiency, reduction of dependencies | SDG 17: Partnerships for the goals | Share of Imports |
| State budgets that are capable of acting, good equipment with meritorious estates | SDG 08: Decent work and economic growth | Market Infrastructure Readiness |
| Social-cultural Dimension | | |
| Criterion (target system goal to respond to global challenge) | Focus SDG | Criterion/ Indicator |
| Establish good governance for acceptance and awareness for RDF uptake | SDG 16: Peace, justice and strong institutions | RDF Acceptance and Awareness |
| Avoidance of poverty and dependencies | SDG 01: No poverty | Dependence of farmers on others |
| Equal opportunities uptake & Market availability and uptake | SDG 4: Quality education | Targeted types of stakeholders involved in the value chain (decentralized, democratic) |
| Geostrategic independency (EU) | SDG 17: Partnerships for the goals<br>SDG 10: Reduced inequalities<br>SDG: 05: Gender equality | Conflict potential of the resources used |
| Abandonment of technologies with significant risks | SDG 16: Peace, justice and strong institutions | Technology Risk |

*Reference: Own table*

# 3 Sustainability Assessment Methodology of RDF

The previous chapter provided an overview of the methodology underpinning the SA-4F, grounded in the Theory of Sustainable Economics. Chapter 3 builds on this foundation by applying and adapting the SA-4F methodology specifically to assess the sustainability of RDF across the three core dimensions of sustainability: economy, ecology, and social impact. This chapter outlines a structured approach for each dimension to define RDF-specific criteria and indicators that address relevant global challenges. It begins by establishing an overarching methodological framework that applies to all criteria and indicators across the three dimensions. This framework includes the definition of comparative scenarios (RDF versus reference scenarios), system boundaries, indicator units, and rating levels. Subsequent subchapters detail the specific criteria and indicators for each sustainability dimension, offering precise derivations for the evaluation of RDF.

## 3.1 General Methodological Framework

### 3.1.1 Scope of comparative scenarios (reference-RDF scenarios)

The reference scenario for this assessment is based on the production and use of synthetic mineral fertilisers in comparison to RDF. The selection of RDF has been clustered by the classification of organic residues recycled by their main nutritional aspect that is the supply of nitrogen (N), phosphorus (P), or potassium (K).[1] For each category, a specific RDF has been selected based on its potential for market entry in NWE. The SA-4F serves as a decision-support tool for all stakeholders across the fertiliser value chain, including policy makers, suppliers, producers, logistics providers, traders, and end-users. Therefore, the selected RDF were chosen for their high market penetration potential. Key factors influencing the selection included supporting legal frameworks, attractive agronomic characteristics that facilitate market adoption, and their relevance to the ReNu2Cycle pot and field trials, which are crucial for assessing their real-world uptake and effectiveness. In the first step, blends of these are excluded due to their analytical complexity but are of interest for follow-up research.

In this study, three RDF (Struvite from municipal wastewater processing (P), Ammonium sulphate produced from anaerobic digestion/ liquid fraction of digestate (LF DIG) separation (N), Potassium (K) fertiliser from sugarcane vinasse) were analysed to determine their

[1] See publication from (Harms et al. 2019) and that "[…] the desired composition in terms of the three main plant nutrients, N, P and K as well as organic carbon differs largely between [ReNu2Cycle] participating regions […]"

sustainability performance in relation to the replacement of the corresponding synthetic produced mineral fertilisers (triple superphosphate ($P_2O_5$), ammonium sulphate ($(NH_4)_2SO_4$), potassium sulphate ($K_2SO_4$)).

*Table 4: Scope of comparative scenarios (reference - RDF scenarios)*

| Plant Nutrients | Reference Scenario | RDF Scenario |
|---|---|---|
| Nitrogen | N fertilisers are primarily produced through the Haber-Bosch process, which synthesizes ammonia by combining nitrogen from the air with hydrogen, typically derived from natural gas. This ammonia is then further processed to create various forms of nitrogen fertilisers, such as urea, ammonium nitrate, and ammonium sulphate. The EU produces nitrogen fertilisers domestically but also imports substantial quantities, particularly due to high energy costs associated with production. Major exporters of nitrogen fertilisers to the EU include countries like Russia, Egypt, and Algeria (Fertilizers Europe 2023). Given its energy-intensive nature, nitrogen fertiliser production faces environmental challenges, prompting the EU to explore sustainable alternatives and improve nitrogen-use efficiency in agriculture (Babcock-Jackson et al. 2023). Synthetic produced ammonium sulphate serves as reference fertiliser. | Rather N-based RDF: Ammonium sulphate can be produced from bioeconomy processes by recovering nitrogen and sulphur from organic waste materials (SYSTEMIC 2018). In biogas production, for example, organic residues undergo anaerobic digestion, releasing ammonia and hydrogen sulphide gases as by-products. These gases are captured and combined in a chemical reaction to produce ammonium sulphate, a valuable nitrogen-sulphur fertiliser. This process not only creates a useful fertiliser but also helps manage waste and reduce emissions from organic materials. By using agricultural or food processing residues, ammonium sulphate production in the bioeconomy supports sustainable resource cycles and reduces dependence on conventional fossil-fuel-derived fertilisers (Herrera et al. 2022). |
| Phosphorus | P in the EU is primarily sourced through imports, as Europe has minimal domestic phosphate rock reserves. The EU depends largely on imports from countries like Morocco, which holds the largest global | Rather P-based RDF: Struvite from municipal wastewater processing: Struvite (magnesium ammonium phosphate ($NH_4MgPO_46H_2O$) formation is a natural phenomenon at wastewater treatment plants (WWTP) and |

| | | |
|---|---|---|
| | reserves, and Russia. Phosphate rock is mined, then processed to produce phosphoric acid, which is used in fertilisers. The production process involves mining, beneficiation (concentrating phosphate minerals), and then chemical treatment. Since phosphorus is essential for agriculture but non-renewable, the EU faces strategic and environmental pressures. To mitigate dependency, the EU is exploring recycled phosphorus from waste sources, like animal manure and sewage sludge, as part of its CE goals. Highly concentrated P fertilisers, such as $P_2O_5$, serves as reference fertiliser (Nedelciu et al. 2020). | occurs at equimolar concentrations of Mg:$NH_4PO_4$ (1:1:1). It is a co-precipitate when magnesium (Mg), ammonium ($[NH_4]^+$), and ortho-phosphate are present in concentrations above the solubility constant. In WWTP with enhanced biological P removal, numerous examples of struvite deposition and its associated problems have been reported. Its deposition clogs pipes through encrustation and scaling, resulting in high costs for operation and maintenance. Therefore, WWTP nowadays implement intentional struvite recovery either on the centrate or the sludge line. While struvite recovery is known to improve the WWTP performance, it also provides a 'bioavailable-P' product which could be a possible substitute for synthetic P fertilisers. |

| | | |
|---|---|---|
| Potassium | K fertilisers are produced primarily from potash ores, which are mined and then refined to create fertilisers such as potassium chloride (KCl), potassium sulphate ($K_2SO_4$), and potassium nitrate ($KNO_3$). The production process involves mining, crushing, and separating the potash minerals to obtain high-purity potassium compounds. The EU has limited potash resources, so it imports a significant portion of its potassium fertilisers, mainly from Canada, Russia, Belarus, and Germany. Given potassium's importance in plant health and the EU's dependency on imports, there is interest in sustainable practices and alternative sources to ensure long-term potassium availability for agriculture (Mikkelsen und Roberts 2021). Synthetic produced $K_2SO_4$ serves as reference fertiliser. | Rather K-based RDF: In Europe, potassium fertiliser can be recovered from vinasse—a nutrient-rich by-product of sugar beet or wine ethanol production—through an integrated biogas and bio-fertiliser system. In this process, vinasse is first subjected to anaerobic digestion to generate biogas, contributing to renewable energy supply. The resulting digestate, rich in potassium and other nutrients, is then treated and concentrated to produce an organo-mineral bio-fertiliser. This bio-fertiliser not only supplies potassium but also adds organic matter that supports soil structure and microbial health. By combining biogas production with nutrient recovery, this circular approach offers a sustainable alternative to imported potassium fertilisers, reduces organic waste, and promotes regional nutrient cycling within European agricultural systems (Balakrishnan 2024). |

*Reference: Own table*

### 3.1.2 System Boundaries

The establishment of system boundaries is a critical step in the SA-4F. The system boundaries define the scope of the analysis and ensure that all relevant factors are considered. For this assessment, the following boundaries will be defined:

- Geographical Scope: The primary geographical focus of this analysis is North-West Europe (NWE), corresponding to the territorial scope of the INTERREG NWE programme. In specific cases, and where data availability necessitates, the broader European Union (EU) may serve as the upper territorial frame of reference. The analysis will generally concentrate on regional contexts where data availability and relevance permit meaningful assessment. However, due to the considerable heterogeneity in agricultural practices and sustainability indicators across regions, this initial assessment will not comprehensively capture regional specificities. Instead, it will rather focus on overarching characteristics common to the participating NWE regions. To reflect local realities more accurately, follow-up research with a stronger regional differentiation is recommended.
- Field Management Practices: The assessment will consider the impacts of field management practices, including but not limited to the methods of soil tillage, crop rotation, fertilisation, and irrigation. This process-oriented approach will examine how field management practices interact with sustainability outcomes, acknowledging that agricultural practices can vary significantly across regions and farm types.

### 3.1.3 Indicator Units

The choice of indicator units is essential for consistency and clarity in the assessment of RDF. Key considerations for selecting indicator units include:

- Unit of Measurement: The standard unit of measurement will be the metric tonne (mt). It is important to distinguish between mt (standard unit) and empirical tons (which may be based on different systems of measurement or local conventions) when reporting results. This distinction ensures the accuracy and comparability of data, especially when evaluating nutrient content.
- Nutrient Content: Special attention will be given to the N, P, and K content of each RDF, as these nutrients are critical to evaluating the effectiveness of fertilisers. Nutrient content will be assessed not only in terms of weight but also in terms of the fertiliser's ability to supply these essential nutrients to crops. For certain types of fertilisers, additional units may be required, especially in the case of liquid fertilisers, where nutrient concentration may vary significantly across products. Highly concentrated P fertilisers, such as $P_2O_5$, serves as reference fertiliser.

### 3.1.4 Rating Levels

In general, to assess RDF against the established criteria, a five-level rating scale with quantitative levels will be used. Such a five-level operationalisation rating scale for assessing the objectives has proven its worth in previous applications, see e.g., the German research project “KoWa – Wärmewende in der kommunalen Energieversorgung” (German funding reference number 03EN3007; funded by the German Federal Ministry for Economic Affairs and Climate Action). A methodological alignment using a ranking method with quantitative scales, can be alternatively used. The scale and operationalisation of the criteria in the form of evaluation levels will be carried out through an iterative discussion process. Each will facilitate a clear understanding of the performance of each RDF against the defined criteria, enabling stakeholders to make informed decisions. The rating levels follow the general trend from Level 1: Very Good, Level 2: Good, Level 3: Neutral, Level 4: Bad, Level 5: Fail (see Table 5 below). The upcoming sub-chapters will provide a detailed explanation of the rating levels fitted to the criteria and their operationalisation.

*Table 5: General methodological rating-level*

| Rating Level | Rating Category | Explanation |
| --- | --- | --- |
| Level 1 | Very Good | Within the scope of the options under consideration, particularly positive effects on the quality of the target are to be expected. If the criterion has quantitative indicators, the option with the best possible value is usually given this rating. |
| Level 2 | Good | Within the scope of the options under consideration, more positive effects on the quality of the target are to be expected. If the criterion has quantitative indicators, the option with above-average values (or those that are close to the target value) is usually given this rating. |
| Level 3 | Neutral | Within the scope of the options under consideration, neither positive nor negative effects on the quality of the target can be predicted or there are no effects. If the criterion has quantitative indicators, the option with average values is usually given this rating. |
| Level 4 | Bad | Within the scope of the options under consideration, more negative effects on the quality of the target are to be expected. If the criterion has quantitative indicators, the option with below-average values (or those that deviate from the target value) is usually given this rating. |
| Level 5 | Fail | Within the scope of the options under consideration, particularly negative effects on the quality of the target are to be expected. If the criterion has quantitative indicators, the option with the worst possible value is usually given this rating. |

*Reference: Own table*

# 3.2 Development of Evaluation Criteria for Assessment of the Ecological Dimension

## 3.2.1 Overview

### *3.2.1.1 Challenges and goals*

The challenges in the ecological dimension result in five goals. The main challenges are global warming, destruction of biodiversity and landscape diversity, and the overuse of resources as well as a threat to human health posed by overuse of fertilisers and the destruction of species and biotope diversity. Goals can be derived from these challenges in order to overcome them. Representative criteria and indicators were selected for each of these goals, which can be used to assess the contribution that a specific fertiliser can be expected to make to achieve the goals. Table 6Fehler! Verweisquelle konnte nicht gefunden werden. summarises these criteria and indicators of the ecological dimension. They are then explained in the subsequent turn for each indicator in detail.

*Table 6: Overview of the ecological dimension with the criterion, Focus SDG and indicator*

| Ecological Dimension | | | |
|---|---|---|---|
| No. | Criterion (to respond to global challenge) | Focus SDG | Indicator |
| 1) | Limitation of climate change regarding the Paris goals | SDG 13: Climate Action | GHG Emissions CO2eq |
| 2) | Nature compatibility: Preservation of the diversity of Mesofauna species in Soils | SDG 15: Life on land | Soil biological degradation: loss of soil biodiversity- Classification scales of CP nematodes spectrum |
| 3) | Nature compatibility: Preservation of the diversity of Microbial Taxa in Soils | SDG 15: Life on land<br>SDG 14 | Biodiversity of bacteria and fungi.<br>Abundance of nutrient cycling (N, P) genes |
| 4) | Sustainable use of soil as a resource | SDG 12: Responsible consumption and production | Nutrient Input vs. Output Ratio) |
| 5) | Healthy living conditions | SDG 3: good health and well being | Concentration of heavy metals in fertiliser |

*Reference: Own table*

## 3.2.2 Criterion (1): Limitation of climate change

### *3.2.2.1 Challenge and Criterion*

Global warming is caused primarily by the increase in GHG in the Earth's atmosphere. The most well-known of the GHGs is $CO_2$ but in the context of agriculture, also Nitrous Oxide ($N_2O$), associated to the microbial nitrogen dynamics in fertilised agricultural soils as well as the emission of Methane ($CH_4$) or its avoidance when adopting proper waste and by-product management. The goal of limiting global temperature rise to well below 2 Degree Celsius (°C), preferably to 1.5°C, compared to pre-industrial levels, as set out in the 2015 Paris Agreement (United Nations Framework Convention on Climate Change 2015).

### *3.2.2.2 Focus SDG*

This criterion primarily aligns with SDG 13: Climate Action, as it addresses the $CO_2$-equivalent ($CO_2$eq) emissions associated with the production, use, and disposal of fertilisers within a defined geographical region. It assesses the climate impact of fertiliser practices across their life cycle. In addition to SDG 13, several other Sustainable Development Goals (SDGs) are interrelated. SDG 2: Zero Hunger is relevant because greenhouse gas emissions from agriculture—including those from fertiliser use—contribute to climate change, which in turn affects food production and security. Reducing such emissions supports the resilience and sustainability of food systems. SDG 9: Industry, Innovation and Infrastructure is addressed through innovations in low-carbon fertiliser technologies and circular economy (CE) solutions that foster environmentally responsible industrial development. SDG 11: Sustainable Cities and Communities is supported by recycling nutrients via organic or waste-derived fertilisers, thereby reducing emissions linked to synthetic fertiliser production. In line with SDG 12: Responsible Consumption and Production, improving fertiliser efficiency and lowering emissions contributes directly to reducing agriculture's carbon footprint. Finally, SDG 17: Partnerships for the Goals is reflected in the need for collaboration between governments, industry, and research institutions to develop and implement sustainable fertiliser strategies that collectively mitigate global emissions.

### *3.2.2.3 Indicator:*

The selected indicator for GHG emissions expressed in $CO_2$eq. It is a key metric used to measure progress towards achieving climate-related goals. It quantifies the amount of GHGs emitted by human activities as expressed by the amount of $CO_2$.

### *3.2.2.4 Geographical scope:*

In a GHG emissions expressed in $CO_2$eq Assessment of fertilisers, the geographical system boundary refers to the physical area or region within which the $CO_2$ impacts of the fertiliser production, use, and disposal are assessed. The RDF perspective should be expanded to include both emissions reduced and emissions additionally emitted throughout the processing chain. The geographical system boundary in a life cycle assessment (LCA) of fertilisers typically includes the a) Production Location: Covers the region where fertilisers are produced, focusing on raw material extraction, manufacturing, energy consumption, and transportation. B) Use Location: Extends to the area where fertilisers are applied, such as farms, assessing impacts on soil health, water quality, and emissions. C) Transportation and Distribution: Includes emissions and energy use related to moving fertilisers from production to market or application sites. D) End-of-Life (EOL): Accounts for the disposal or recycling of fertilisers, particularly if they contribute to pollution or are part of a CE. E) Regional or National Boundaries: Focuses on specific regions, such as a federal state or agricultural area, reflecting local conditions, regulations, and environmental factors. F) Global Boundaries: Covers global impacts, particularly in international supply chains, considering raw material extraction, energy use, and emissions across multiple countries (Gaidajis und Kakanis 2021; Reich 2024).

#### *3.2.2.5 How to measure:*

Data for the LCA of fertilisers will be gathered using the following structured approach: Desk Research and Data Repositories: The data will be collected through desk research, utilizing data warehouses and established databases such as Global Emission Model for Integrated Systems (GEMIS). Relevant literature, including reports from synergy projects and the Thünen Institute, will be analysed to provide baseline data on GHG emissions from various stages of the fertiliser lifecycle.

Data from ReNu2Cycle: The ReNu2Cycle project itself will provide additional primary data through its pot and field experiments with RDF. These experiments will yield on-site data, such as emissions from the application of RDF in agricultural settings, which will be integrated into the LCA to enhance accuracy. ReNu2Cycle will produce specific LCA Reports: The environmental impact of nutrients and CO2 emissions will be delivered through the deliverable report D1.2.3 (LCA), which provides a comprehensive evaluation of the environmental footprint associated with RDF use.

In terms of system boundaries, this includes emissions from key stages such as raw material extraction, processing, production, and transport of the fertiliser to the farm gate. Emissions during the application phase (e.g., nitrous oxide release) may be considered separately, depending on data availability and comparability. The goal is to capture the most relevant and quantifiable stages contributing to the fertiliser's carbon footprint, ensuring consistency across RDF and synthetic fertiliser assessments. Indirect emissions (e.g., land use change or energy mix) are included where data allows and where they significantly influence results.

This report will play a critical role in supplementing data and offering insights into the broader environmental impacts of the fertiliser lifecycle. There will be project exchange under the European Sustainable Nutrient Initiative (ESNI) Working Group on LCA to exchange methodologies and foster collaboration.

#### *3.2.2.6 Data availability*

In other projects it was possible to access a sufficient amount of LCA data to define rating levels by quantitative thresholds. This was the initial aim of the project team for the Criterion of GHG-emissions. However, the expert discussions have shown that the amount of LCA data on fertilisers is very limited. For this reason, the project team decided within this version 1.0 to directly compare the fertilisers and rank them.

#### *3.2.2.7 Measurement units:*

The chosen unit is $CO_2$eq per mt of fertiliser product.

#### *3.2.2.8 Rating levels:*

A 5-level ranking system is employed and its levels are defined on a qualitative basis. A methodological alignment of rating levels using a ranking method where the production method with the lowest $CO_2$eq (whether conventional, untreated organic residual fertilisers, or RDF processing technology) ranks first. The rating levels in this matrix are based on a comparative evaluation of recycling-derived fertilisers (RDF) in relation to conventional mineral fertilisers, which serve as the default reference level or baseline. This baseline reflects typical practices, particularly the production and application of synthetic fertilisers based on current industry standards and available life cycle inventory data. "Neutral" (Level 3) therefore corresponds to an RDF option performing on par with conventional fertilisers in terms of GHG emissions per functional unit (e.g., per kg nutrient or per hectare). Ratings above or below this level reflect relatively better or worse performance in comparison to this established reference. This comparative framing enables a differentiated and practical interpretation of sustainability impacts across options under consideration. This assessment uses a qualitative rating approach, meaning the classification into levels (Very Good to Fail) is based on expert judgment informed by available data and contextual interpretation rather than fixed numerical thresholds. While no absolute $CO_2$eq values define each category, comparative trends—such as expected reductions or increases in GHG emissions relative to conventional mineral fertilisers—form the basis for assigning a level. For example, RDF options demonstrating a clear and evidence-supported GHG advantage are rated as "Very Good" or "Good," while options performing similarly to conventional fertilisers are rated as "Neutral." The assignment considers the direction and relative magnitude of change, consistency of available data, and relevance within the regional context of NWE. As more quantified data become available, this framework could be refined to integrate semi-quantitative or threshold-based elements.

*Table 7: Five-level rating system levels on production method*

| Rating Level | Explanation of comparative scope |
|---|---|
| Level 1: Very Good | Within the scope of the options under consideration, particularly positive effects on the quality of the target are to be expected. Best Performer |
| Level 2: Good | Within the scope of the options under consideration, more positive effects on the quality of the target are to be expected. |
| Level 3: Neutral | Within the scope of the options under consideration, neither positive nor negative effects on the quality of the target can be predicted or there are no effects. Neutral Performer |
| Level 4: Bad | Within the scope of the options under consideration, more negative effects on the quality of the target are to be expected. |
| Level 5: Fail | Within the scope of the options under consideration, particularly negative effects on the quality of the target are to be expected. Worst Performer |

*Reference: Own table*

### 3.2.3 Criterion (2): Nature compatibility: Preservation of the diversity of mesofauna species in soils

#### *3.2.3.1 Challenge and Criterion:*

In previous projects two criteria for the user of resources have been used. To the expert team of ReNu2Cycle it seemed more important to use two criteria to ensure nature compatibility. Therefore, this project uses the criteria "Preservation of the diversity of mesofauna species in soil" as well as "Preservation of the diversity of Microbial Taxa in Soils".

The use of fertilisers has direct impacts on soil quality and health, which are directly linked to biodiversity, soil productivity and climate resilience. Overuse can result in destruction of biodiversity and landscape diversity. To address this challenge, the criterion is to preserve the diversity of mesofauna species in soils like nematode communities as reference to asses soil biodiversity and ecosystem function.

#### *3.2.3.2 Focus SDG:*

The assessment of coloniser-persister (C-P) nematodes is closely related to SDG 15 (Life on Land) because these nematodes serve as vital indicators of soil health, which is a critical component of terrestrial ecosystems. SDG 15 emphasizes the conservation and restoration of land ecosystems, including soil health, to sustain biodiversity and ecosystem services. C-

P nematodes are integral to soil biodiversity, playing a key role in nutrient cycling, organic matter decomposition, and the overall functioning of soil ecosystems. Monitoring their populations can provide valuable insights into soil quality, revealing the impact of land management practices, land degradation, and biodiversity loss. By assessing C-P nematodes, we can better understand the state of soil ecosystems, ensuring that land use practices align with the goal of protecting and restoring life on land, ultimately contributing to the achievement of SDG 15. With soil health being essential for ecosystem services such as food production, carbon sequestration and water filtration, SDG 12 (Responsible Consumption and Production) and SDG 14 are Focus SDG.

#### *3.2.3.3 Indicator:*

The assessment of C-P nematodes uses several key metrics:

- Nematode Abundance: Measures the total nematode population in soil, indicating microbial activity.
- Nematode Diversity: Evaluates species variety, with higher diversity linked to healthier soil.
- Community Structure: Analyses the balance of functional groups (e.g., C-P vs. oligotrophic nematodes) to assess nutrient availability and soil conditions.
- Nematode Functional Index (NFI): Assesses soil health through the distribution of functional groups.
- Nematode: Bacteria/Fungi Ratios: Indicates microbial activity and nutrient cycling efficiency.
- These metrics help gauge soil health, nutrient cycling, and biodiversity, aligning with SDG 15 (Life on Land).

#### *3.2.3.4 Geographical scope:*

The problem of soil has direct impacts locally exposing resources and vulnerabilities. The measurement and monitoring focus is therefore regional — it could pertain to national levels depending on the scope of the data repository and analysis.

#### *3.2.3.5 How to measure:*

Diversity and community structure of nematodes serve as indicators for soil health. Several metrics can be used to monitor and assess nematode communities. They are:

(1) Total abundance estimation
(2) Nematode indices (maturity index, enrichment index, channel index, structure index
(3) Nematode diversity (alpha and beta diversity indices)
(4) Relative abundance
(5) C-P scale assignment
(6) Food web diagnostics

#### 3.2.3.6 Data availability

Data on C-P nematodes is gathered through soil trials by collecting samples from different project plot trials with varying RDF and agriculture cultivations. These trials, which include factors like fertilisation or crop rotation, help assess how these practices influence nematode populations. Multiple samples are taken to track fluctuations in nematode abundance, diversity, and community structure. The data are enriched by secondary data from literature.

#### 3.2.3.7 Measurement units:

The chosen measurement unit are directly to what they measure

(1) Number of nematodes per 100 cubic centimetres ($cm^3$) soil
(2) Operational taxonomic units (OTU) (family richness of a sample)
(3) Total OTUs in a sample
(4) No. of individual nematode trophic group /Total no. of nematodes in the sample
(5) Trophic groups

#### 3.2.3.8 Rating levels:

The 5-level rating of the C-P scale is used as a rating system to assess the state of soil. It categorizes nematodes into 'colonizer' (r-strategists) and 'persister' (K-strategists) groups, which can give insights into soil disturbance, nutrient availability, and ecological resilience. The 5-level rating system levels are defined as follows:

*Table 8: Five-level rating system levels on C-P scale*

| Rating Level | Rating Category | Explanation |
|---|---|---|
| Level 1 | C-P 5,4 | Soil in excellent health, dominated by colonizer nematodes. |
| Level 2 | C-P 4,3 | Soil is in good condition, but some disturbance may have occurred. |
| Level 3 | C-P 2,3 | Moderate disturbance, possibly reflecting altered soil function. |
| Level 4 | C-P 2,1 | Significant disturbance or degradation of soil health |
| Level 5 | C-P 1 | Highly disturbed soil with few, if any, nematodes. |

*Reference: Own table*

### 3.2.4 Criterion (3): Nature compatibility: Preservation of the diversity of Microbial Taxa in Soils

#### 3.2.4.1 Challenge and Criterion:

In addition to preservation of the diversity of mesofauna species in soil, the overconsumption of minerals and intensive agricultural inputs, presents significant risks microbial taxa. Microbial Taxa in soils like fungal communities, in particular, play a crucial role in nutrient cycling (especially nitrogen and phosphorus) and maintaining the biodiversity of soils. When soil ecosystems are disrupted through overuse, microbial taxa diversity can be lost, with cascading effects on soil fertility, carbon sequestration, and broader ecosystem stability.

#### 3.2.4.2 Focus SDG:

The primarily SDG this criterion focusses on is SDG 15 (Life on land). Microbial Taxa play a central role in the cycling of essential nutrients (e.g., nitrogen, phosphorus, and carbon) in the environment. Soil microbes break down organic matter, decompose plant residues, and recycle nutrients, making them available to plants. This natural process reduces the need for fertilisers. Preserving microbial taxa, including fungi involved in nitrogen and phosphorus cycling, can enhance the resilience of ecosystems and ensure that they continue to provide essential services, such as nutrient cycling and carbon sequestration.

#### 3.2.4.3 Indicator:

Promoting the preservation of microbial diversity can be assessed through soil stoichiometry, particularly the relationship between carbon (C):N ratios. As an indicator it assesses, indicator genes after application of fertiliser. The balance of three key nutrients—C, N, and P—in soil has profound implications for nutrient cycling, microbial activity, and plant growth.

#### 3.2.4.4 Geographical scope:

The preservation of the diversity of Microbial Taxa has direct impacts on local soils and its resources. Therefore, measurement and monitoring focus is regional. Within the ReNu2Cycle project the project team uses results from field and pot trials to evaluate the impact of specific RDF in contrast to other fertilisers on soil health.

#### 3.2.4.5 How to measure:

To measure the diversity of bacterial and fungal communities and the abundance of key genes two approaches can be used i) 16S/ITS next generation sequencing or ii) 16S/ITS DNA fingerprinting.

#### 3.2.4.6 Data Availability

Data is gathered through soil trials by collecting samples from different project plot trials with varying RDF and agriculture cultivations. These trials, which include factors like fertilisation or crop rotation, help assess how these practices influence nematode populations. Multiple samples are taken to track fluctuations of bacterial and fungal communities and the abundance of key genes. The data are enriched by secondary data from literature.

#### 3.2.4.7 Measurement units:

The chosen unit are the alpha (Shannon index) and beta diversity (PCoA/NMDS, ADONIS), and gene copy number per g soil OR copy of 16S.

#### 3.2.4.8 Rating levels:

The 5-level rating system employed and measured units are defined:

*Table 9: Five-level rating system levels on diversity of bacterial and fungal communities and the abundance of key genes*

| Rating Level | Rating Category | Explanation |
|---|---|---|
| Level 1 | Very Good | Improved alpha diversity by +20%, increased P mineralization by +20%, reduced denitrification by +20% |
| Level 2 | Good | Improved alpha diversity by +10%, increased P mineralization by +10%, reduced denitrification by +10% |
| Level 3 | Neutral | No change |
| Level 4 | Bad | Reduced alpha diversity by +10%, decreased P mineralization by +10%, increased denitrification by +10% |
| Level 5 | Fail | Reduced alpha diversity by +20%, decreased P mineralization by +20%, increased denitrification by +20% |

*Reference: Own table*

### 3.2.5 Criterion (4) Sustainable use of soil as a resource

#### 3.2.5.1 Challenge and Criterion:

The use of fertilisers has direct impacts on soil quality, which is directly linked to soil productivity. Soil is considered a non-renewable resource because its formation process is extremely slow, taking hundreds to thousands of years to develop just a few centimetres of fertile soil. Factors such as erosion, urbanization, and unsustainable agricultural practices can degrade soil much faster than it can regenerate. Once soil is eroded or degraded, it cannot be easily replaced, making its loss irreversible on human timescales. This makes soil a finite resource that requires careful management to preserve its quality and productivity.

#### 3.2.5.2 Focus SDG:

The criterion is directly related to SDG 12 (Responsible Consumption and Production) that aims to promote sustainable production and consumption. This means protection and improvement of soil quality is seen as part of the responsible use of resources. Soil is a resource that can be quickly degraded if not used properly.

#### 3.2.5.3 Indicator:

This indicator aims to reflect the material footprint of fertiliser use with respect to soil and environmental health, with a focus on nutrient cycling efficiency (Nutrient Input vs. Output Ratio). The selected metric, 'Nutrient Input vs. Output Ratio', compares the amount of nutrients added to the soil—via fertilisers, organic amendments, and other sources—with the nutrients removed by crop harvests.

A ratio greater than 1 indicates nutrient accumulation, which may suggest a risk of nutrient losses to the environment (e.g., through leaching, runoff, volatilisation), particularly for highly mobile nutrients like nitrate. In contrast, a ratio below 1 may indicate nutrient depletion, potentially leading to soil degradation and declining soil fertility over time. The indicator helps assess whether fertiliser practices are contributing to sustainable nutrient use or to environmental pressures. This ratio can be applied in both controlled pot experiments and field trials, depending on the fertiliser type and context. For nitrogen, it may be relevant to additionally evaluate the Nitrogen Fertiliser Replacement Value (NFRV) of RDF compared to conventional mineral fertilisers, particularly when assessing substitution potential.

#### 3.2.5.4 Geographical scope:

Issues related to nutrient balances and soil degradation—such as nutrient surpluses, depletion, and erosion—have strong location-specific impacts, reflecting regional differences in soil type, climate, and farming practices. Therefore, the assessment is primarily conducted at the regional level. However, where relevant and supported by available data, national-level data may also be considered. The geographical focus remains aligned with the INTERREG NWE programme area, although the methodology may apply more broadly.

#### 3.2.5.5 How to measure:

The Nutrient Input vs. Output Ratio will be calculated using the following steps:

Nutrient Inputs: Track all nutrient sources applied to the soil, including mineral fertilisers, composts, digestates, manures, and other amendments.

Nutrient Outputs: Estimate nutrient uptake by crops by multiplying measured crop yields with established nutrient content values (based on lab analysis or reference tables).

Calculate the Ratio: The ratio is determined by dividing the total nutrient input by the total crop nutrient output. Results will be interpreted in context, accounting for nutrient type.

For nitrate and other mobile nutrients, accumulation is less likely; a high ratio more likely signals over-fertilisation and environmental risk. For phosphorus or potassium, which are less mobile, accumulation may indicate soil storage or inefficient uptake.

This indicator can be applied alongside other tools to support a comprehensive understanding of fertiliser sustainability.

#### *3.2.5.6 Data Availability*

As with other sustainability criteria such as GHG emissions, data availability on nutrient footprints and fertiliser life cycle impacts is currently limited. Due to these constraints, the project applies a direct comparative approach, using available data to rank fertiliser products qualitatively based on field and pot trials as experimental evidences where possible from the project, expert judgment, literature values, etc. This approach will be refined as more data become accessible through field trials and further research.

#### *3.2.5.7 Rating levels:*

A 5-level ranking system is employed and its levels are defined on a qualitative basis. This indicator evaluates the balance between nutrients applied to the soil and those removed through crop harvests, using the Nutrient Input vs. Output Ratio as a proxy for sustainable nutrient management. The indicator is interpreted within a qualitative rating matrix, which reflects how well a fertiliser product supports efficient nutrient cycling, soil health, and environmental protection.

The ideal benchmark is a ratio close to 1, indicating that nutrient inputs closely match crop nutrient uptake. This balance minimises the risk of both environmental losses (e.g., through nitrate leaching, phosphorus runoff, or gaseous nitrogen emissions) and long-term soil degradation due to nutrient depletion.

*Table 10: Five-level rating system levels on cumulative material footprint*

| Rating Level | Rating Category | Explanation of comparative scope |
|---|---|---|
| Level 1 | Very Good | (Best Performer): Nutrient input/output ratio is close to 1, indicating a well-balanced system. Nutrient losses and depletion risks are minimal. Practices promote long-term soil fertility and environmental protection. |
| Level 2 | Good | Ratio is slightly above or below 1, indicating minor nutrient surplus or deficit. Overall, the system remains relatively efficient, with manageable environmental or soil risks. |

| | | |
|---|---|---|
| Level 3 | Neutral | (Neutral Performer): Ratio deviates moderately from 1 (e.g., either surplus or deficit), but impacts are uncertain or vary by context (e.g., nutrient type, soil conditions). No strong sustainability advantage or disadvantage is evident. |
| Level 4 | Bad | Ratio indicates substantial surplus or deficit. High risk of nutrient losses to the environment (e.g., nitrate leaching) or signs of soil nutrient depletion over time. |
| Level 5 | Fail | (Worst Performer): Ratio is significantly imbalanced. Severe nutrient surpluses with high environmental damage potential or sustained nutrient deficits threatening long-term soil health and productivity. |

*Reference: Own table*

## 3.2.6 Criterion (5): Healthy Life Conditions

### *3.2.6.1 Challenge and Criterion:*

The challenges focus on potential risks to human health arising from pollutants associated with fertilisers, particularly heavy metals that can lead to soil contamination, plant uptake, and groundwater pollution. These risks are especially relevant when using recycling-derived fertilisers (RDFs) produced from organic or waste-based sources, which may contain residual contaminants depending on their origin and treatment process.

This section compares RDFs with conventional mineral fertilisers, with a focus on their contribution to healthy life conditions, assessed through heavy metal concentrations in the product. Compliance is measured against legally defined thresholds, as specified in the EU Fertilising Products Regulation (REGULATION (EU) 2019/1009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 2019). The regulation defines the maximum allowable concentrations of selected pollutants (e.g., cadmium, lead, arsenic, mercury, chromium VI, nickel) in Milligrams per kilogram (mg/kg) of dry matter, ensuring product safety at the point of sale and use.

While the regulation governs product quality, soil health and environmental accumulation are addressed through national or regional agro-environmental monitoring. In the RenU2Cycle project, RDF compliance is measured through lab analyses, pot and field trials, and benchmarked against literature-based data for conventional fertilisers, feeding into a structured sustainability rating system.

#### *3.2.6.2 Focus SDG:*

The need for healthy life conditions is essential for ensuring that people can live productive and fulfilling lives. The goals of SDG 3: Good Health and Well-being aims to ensure health and well-being for all at all ages. Achieving this goal requires addressing both the direct and indirect factors that affect public health, including environmental pollution, lifestyle choices, and access to resources.

#### *3.2.6.3 Indicator:*

To assess healthy life conditions the used indicator measures concentration of pollutants in application on the field. Mainly heavy metal concentrations: Cadmium (Cd), Lead (Pb), Arsenic (As), Mercury (Hg), Nickel (Ni), Chromium VI (Cr(VI)) in compliance with legal thresholds (REGULATION (EU) 2019/1009 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003 2019) are taken as baseline scenario. Indicator name is Heavy Metal Compliance Index.

Pathogen levels (e.g., E. coli, Salmonella, or parasites) and soil health indicators (such as soil organic carbon content and soil pH), although important for overall fertiliser evaluation, are considered out of scope for this specific assessment.

#### *3.2.6.4 Geographical scope:*

While the challenge of human health is a global one, the impacts and urgency of these challenges can vary significantly depending on local, regional, and national contexts. The geographical scope of fertiliser application refers to the spatial extent and areas where fertilisers are applied, influencing both environmental and agricultural outcomes. The geographical scope includes trial sites across different partner regions, allowing us to assess performance under varying soil and climate conditions.

#### *3.2.6.5 How to measure:*

To measure compliance of RDF in the ReNu2Cycle project, we combine laboratory testing, pot and field trials, and literature-based reference scenarios. RDF samples are collected from producers and analysed in accredited labs for heavy metals (Cd, Pb, Hg, As, Cr(VI), Ni) and, where relevant, pathogens, in accordance with EU Fertilising Products Regulation (EU 2019/1009). Soil and plant samples from trials are monitored to assess pollutant accumulation, mobility, and crop uptake. All RDFs are traced back to their input materials and processing methods for quality assurance. As a reference, we integrate data from desktop studies on conventional mineral fertilisers to benchmark environmental and health performance. All results feed into a five-level sustainability rating system, enabling comparative assessment and communication with policy stakeholders.

### 3.2.6.6 Data availability:

See 3.2.6.5. Data availability is generally good through collaboration with RDF producers and controlled trials, though some gaps remain in long-term accumulation effects and variability across RDF batches.

### 3.2.6.7 Measurement units:

Heavy Metal Units: mg/kg or parts per million (ppm) dry matter

### 3.2.6.8 Rating levels:

A five-level rating system is used to assess the concentration of heavy metals in fertilisers. Level 1 corresponds to the maximum legal threshold—that is, 100% of the permitted limit under the EU Fertilising Products Regulation (Regulation (EU) 2019/1009). The higher levels (Levels 2 to 5) represent increasing levels of quality, based on progressively lower percentages of these legal limits. The specific threshold values defined by the regulation are:

- Cd: 1.5 mg/kg dry matter
- Cr(VI): 2.0 mg/kg dry matter
- Hg: 1.0 mg/kg dry matter
- Pb: 120.0 mg/kg dry matter
- Ni: 100.0 mg/kg dry matter
- As: 40.0 mg/kg dry matter

Each rating level is determined by comparing the measured concentration of each heavy metal to its respective threshold. To qualify for a specific level, a fertiliser must stay below the required percentage for all six metals. How is the overall level determined? Using a strict approach, the lowest individual rating among all six heavy metals determines the product's overall level.

*Table 11: Five-level rating system for Healthy Life Conditions*

| Rating Level | Rating category: Heavy Metals |
|---|---|
| | Heavy Metals (mg/kg or ppm)! |
| Level 1 | Values are 100 percent of the limit value or just below - just about acceptable. |
| Level 2 | Values are below 75 percent of the limit value - slightly better than required. |

| | |
|---|---|
| Level 3 | Values are below 50 percent - solid quality. |
| Level 4 | Values are below 25 percent - very low contamination. |
| Level 5 | Values are below 10 percent - top quality, hardly any heavy metals detectable. |

*Reference: Own table*

# 3.3 Development of Evaluation Criteria for Assessment of the Economic Dimension

## 3.3.1 Overview

### *3.3.1.1 Challenges and goals*

The challenges in the economic dimension result in five overarching goals. The main challenges relate to negative developments on the labour market, insufficient satisfaction of basic needs, instability of monetary value and financial markets, as well as imbalances in global trade, dependencies, underdevelopment as well as public debt, inadequate equipment with merit goods. Goals can be derived from these challenges in order to overcome them. Representative criteria and indicators were selected for each of these goals, which can be used to assess the contribution that a type of fertiliser can be expected to make to achieve the objectives. Table 12 summarises these criteria and indicators of the economic dimension. They are then explained in the subsequent turn for each indicator in detail.

*Table 12: Overview of the economic dimension with criterion, Focus SDG and indicator*

| Economic Dimension | | | |
|---|---|---|---|
| No. | Criterion (to respond to global challenge) | Focus SDG | Indicator |
| 6) | Decent work: secure jobs, no vulnerable employment | SDG 08: Decent work and economic growth | Regional value added within the supply chains |
| 7) | Satisfaction of basic needs: with sustainable products | No SDG | Availability & accessibility in terms of market penetration (perspective farmer) in regions |
| 8) | Stability of monetary value and financial markets, | No SDG | Appropriate prices for demand and supply |

| | | | |
|---|---|---|---|
| | appropriate concentration, low externalities | | |
| 9) | Foreign trade balance, high level of self-sufficiency, reduction of dependencies | SDG 17: Partnerships for the goals | Share of Imports |
| 10) | State budgets that are capable of acting, good equipment with meritorious estates | SDG 16<br>SDG 17: Partnerships for the goals | Market Infrastructure Readiness |

*Reference: Own table*

## 3.3.2 Criterion (6): Regional value added within supply chains

### *3.3.2.1 Challenge and Criterion:*

The challenge relates to negative developments on the labour market, which are linked to employment shifts, supply chain dynamics, and the economic impact of fertiliser utilization in related industries such as agriculture and waste management. Therefore, the criterion focuses on the economic effects within the region.

A project analysing the value added by renewable Energies focuses on employment effects as well as monetary cashflows regarding investments and payments within the region. They also include municipal tax payments by investors. The team emphasizes on the importance of the net effect of renewable energies on the regional value added. Therefore, intermediate products also need to be included in the analysis (Hirschl et al. 2015: 58).

### *3.3.2.2 Focus SDG:*

The fertiliser use in supply chains only indirectly connects to SDG 8 (Decent work and economic growth). SDG 8 seeks to promote inclusive and sustainable economic growth, employment, and decent work for all. More importantly, the criterion reflects on the requirements of Art. 147 f TFEU (high level of employment) as well as Art. 3 TEU (balanced economic growth). The RDF use is integrated into industries such as fertiliser production, waste management, and can have significant implications for job creation, job quality, and economic development.

### *3.3.2.3 Indicator:*

The indicator evaluates the effects of a specific fertilisers on the regional value added within the supply chains of the fertiliser. Within the scope of the ReNu2Cycle Project it is not feasible to calculate the effects on the regional value added for each fertiliser. However, with the expert knowledge from stakeholders it is possible to conclude if the use of a specific product has positive impact on the value crafted in the region.

#### *3.3.2.4 Geographical scope:*

The question of the geographic scope is directly related to value chains as it links to question if the RDF production takes place inside or outside the region.[2] Moreover, it is necessary to have a closer look what process steps take place in the region when applying RDF. In other projects it was assumed that a supply chain has a positive impact on the regional value added if most of the economic value creation takes place close by.

The geographical scope of the regional value added should be related/ compatible with the system boundaries of the LCA studies. However, this indicator focuses on regional effects whereas e.g., GHG-emissions measure global effect which will also have a regional outcome in the future.

#### *3.3.2.5 Example*

If a fertiliser is produced outside Europe, it can be assumed that a major part of the value added is also induced outside Europe and not in the region. The same would apply for using fossil fuels in domestic heating, as they have to be imported and the value adding takes place outside Europe.

#### *3.3.2.6 Data availability*

The regional added value can be quantified in monetary terms (e.g., euros) of total value added. Although symmetric input-output tables as well as supply and use tables are reported as part of the European system of national and regional accounts in the EU the current input-output framework only allows a breakdown by components of products but not by their production process (European Union 2013). RDF cannot easily be distinguished in the statistics from conventional fertilisers. Due to the scope of the project, is does not seem feasible to perform a calculation of the regional value added in the field trials. This could be done, when the market for RDF has developed further. A similar approach was used to calculate the effects on regions and municipalities using renewable energies in Germany (Hirschl et al. 2015).

#### *3.3.2.7 How to measure:*

Supply chains must be analysed regarding their regional value added. For that purpose, supply chain mapping (Mubarik et al. 2023) can be used in the living lab approach (LLA) to capture different perspectives on the contribution to the added value. Workshops, surveys and expert interviews can be used to analyse the supply chain map.

[2] For the purpose of the SA-4F a region is characterised by a multi-perspective approach that accounts for real transport barriers, distance- and cost-based segmentation as well as sector specific economic and cultural interdependencies.

### *3.3.2.8 Rating levels:*

The 5-level rating system is employed, and levels used to measure regional- and value added within the supply chains are defined as follows:

*Table 13: Five-level rating system levels for regional value added*

| Rating Level | Rating Category | Explanation |
|---|---|---|
| Level 1 | Very Good | The major part of value added in the economic process of fertiliser production is added in the region. Positive employment effects are primarily expected from regional stakeholders if the supply option is implemented. This can be assumed if most of the added value induced by this supply option takes place in the region and primarily regional private and public stakeholders, such as municipal utilities, are involved in the implementation. |
| Level 2 | Good | A large portion of value added is added in the region. Mixed local and regional stakeholder involvement, some imports involved. |
| Level 3 | Neutral | Value added primarily across regions, but within Europe. Positive employment effects are expected in Europe, when the supply option is implemented. Most of the added value induced by this supply option takes place across regions, but within the country. The implementation primarily involves supra-regional companies (utilities) based in the region. |
| Level 4 | Bad | Limited value added in the region, significant external influence. Employment effects are less certain, reliance on companies from abroad and imports. |
| Level 5 | Fail | This Level is used if the majority of the added value induced by this supply option takes place outside Europe and is imported. This is the case, for example, if the fertilisers sources are largely imported from abroad. |

*Reference: Own table*

### *3.3.2.9 Specifications (Synergies):*

We expect synergies in the analysing process with criterion (7) because for both criteria a supply chain mapping is needed. Moreover, synergies with D.1.1.1 (substance flow analysis) as a basis for Supply chain mapping are expected.

### 3.3.3 Criterion (7): Availability and accessibility in terms of market penetration

#### 3.3.3.1 Challenge and Criterion:

The global challenge considers the satisfaction of basic needs with sustainable products. In terms of the framework conditions of RDF this challenge can be met if sustainable fertilisers are available to cover the needs of farmers and thereby contribute to a sufficient food and crop supply. The criterion aims to capture availability and accessibility of fertilisers (including RDF) in terms of penetration from the perspective of farmers across the NWE regions.

#### 3.3.3.2 Focus SDG:

The challenge is loosely connected to SDG 9: Industry, Innovation, and Infrastructure, which aims to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. In this context, providing sustainable products involves addressing both the fundamental needs of communities (such as food, water, energy, and shelter) and ensuring that these products are produced in a sustainable and resource-efficient manner.

It is worth noticing, that this criterion is not strongly related to the SDG. However, this criterion is rather related to the objectives of the EU's Common Agricultural Policy, including and focusing on the operation and development of the internal market for agricultural products (TFEU: Art. 38). Moreover, Art. 39 c+d of the TFEU name the objectives to stabilise markets and to assure the availability of supplies.

#### 3.3.3.3 Indicator:

The adopted indicator measures RDF' availability and their accessibility in terms of market penetration (perspective farmer) in the relevant (regional) market. Based on the legal definition (Commission notice on the definition of relevant market for the purposes of Community competition law 1997) the consortium defines: A relevant product market comprises all those products which are regarded as interchangeable or substitutable by the *farmer*, by reason of the products' characteristics, and their intended use.

#### 3.3.3.4 Geographical scope:

The geographical scope regarding mineral fertilisers and RDF availability and accessibility can vary widely depending on the region, the specific supply chain dynamics, and the policy frameworks in place. However, the way RDF are produced, traded, and utilized can span multiple geographical areas, with specific implications for local, regional, and international levels. For the purpose of the analysis and based on the legal definition (Commission notice on the definition of relevant market for the purposes of Community competition law 1997) the consortium defines: The relevant geographic market comprises the area in which the undertakings concerned are involved in the supply and demand of products, in which the conditions of applying the products are sufficiently homogeneous.

### 3.3.3.5 Data availability

Information on the supply chains will be available through D.1.1.1 (substance flow analysis). Information on market conditions as mentioned below have to be gained through the living labs and discussions with stakeholders in the field.

### 3.3.3.6 How to measure:

The basis to evaluate the market conditions for fertilisers is the mapping of supply chains as it is necessary for criterion (6) regional value added. In addition, market conditions from a meso perspective should be discussed. Therefore, the framework of the structural analysis of industries (Porter's five forces) might be used (Porter 2004a; 2004b).

RDF producers have the role of substitutes, meaning they put competitive pressure on existing fertiliser producers. Farmers have the main role of buyers and fertiliser producers. Their bargaining power depends on the buyer concentration versus the concentration of fertiliser producers, their buying volume, the switching costs to a new supplier (including costs for new fertilisation machinery) or a substitute as well as their ability to backward integrate (Porter 2004a: 6).

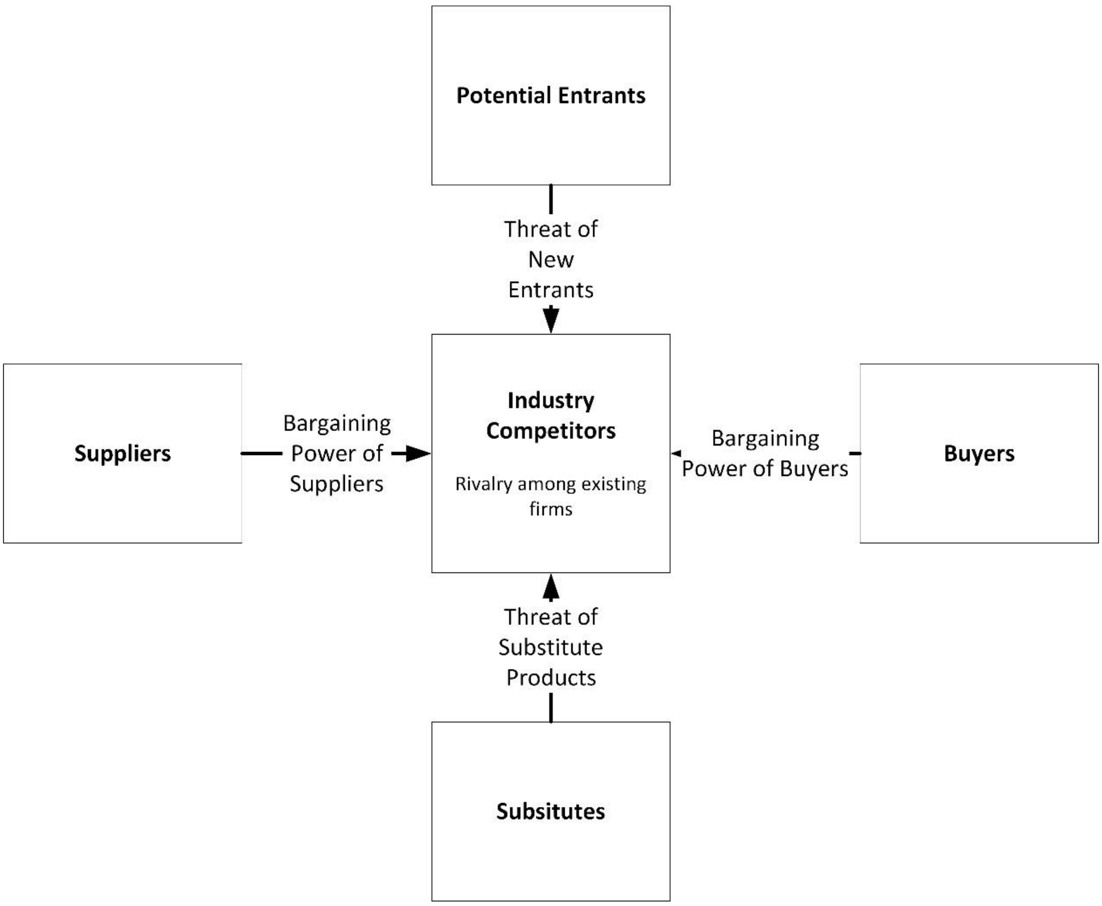


Figure 2: 17 Structural analysis of industries (Porter's five forces, Porter 2004a: 5)

An expert team should evaluate the market structure and the driving forces for each fertiliser group (N, P, K-based) per region. Information should be gathered through desktop research and interviews. The main questions are if the available quantities match the demand in the region.

#### 3.3.3.7 Rating levels:

A 5-level rating system is employed to assess RDF availability and their accessibility. It has a focus on regional and cross-border trade aspects of RDF components. The different levels are defined:

*Table 14: Five-level rating system levels for RDF availability and accessibility*

| Rating Level | Rating Category | Explanation |
|---|---|---|
| Level 1 | Local Production, Cross-Border Trade Equal | RDF is locally produced within the region, and there is a balance between local supply and cross-border trade. Both production and trade are sufficient to meet the demand. |
| Level 2 | Local Production, Cross-Border Trade Limited | RDF is locally produced, but the availability of cross-border trade is limited or inconsistent. This means that, while local production may cover a significant portion of demand, cross-border supply is occurring or due to (short-term) shortages caused by logistics, or capacity issues. |
| Level 3 | Regional/Cross-Regional Availability Limited/ Not Sufficient | RDF are regionally or cross-regionally available, but the amount produced or traded is insufficient to meet the full demand. |
| Level 4 | Production and Trade Insufficient Within Europe | RDF are insufficiently produced or traded within Europe, and as a result, regions face shortages. Imports from outside of Europe become necessary to meet local demand. |
| Level 5 | Complete Reliance on Imports Outside Europe | RDF or fertiliser is not produced locally or regionally, and the main source of supply is from outside Europe. The region is dependent on external markets for RDF/ fertiliser, likely due to lack of infrastructure, policy restrictions, or insufficient local capacity. |

*Reference: Own table*

### *3.3.3.8 Specifications (Synergies):*

We expect synergies in the analysing process with criterion (6) because for both criteria a supply chain mapping is needed.

## 3.3.4 Criterion (8): Appropriate prices for demand and supply

### *3.3.4.1 Challenge and Criterion:*

The global challenge addresses stability of monetary value and financial markets, appropriate concentration and low externalities. In regard with the fertiliser's market, one needs to consider the appropriate prices for demand and supply of fertilisers, especially RDF.

### *3.3.4.2 Focus SDG:*

SDG 12 Responsible Consumption and Production reflects the principles of responsible consumption, efficient supply chains, and environmental sustainability. However, the criterion of appropriate pricing is only loosely connected to SDG. More importantly, this criterion reflects on the EU-objectives to stabilise markets and to ensure that supplies reach consumers at reasonable prices (TFEU: Art. 39 c+d) which is based on the price stability objective of the internal market according to Art. 3 TEU. Pricing mechanisms are pivotal because besides easing market accessibility they determine affordability and also incentivize or disincentivize sustainable practices.

Prices of mineral fertilisers have been volatile during the last years.

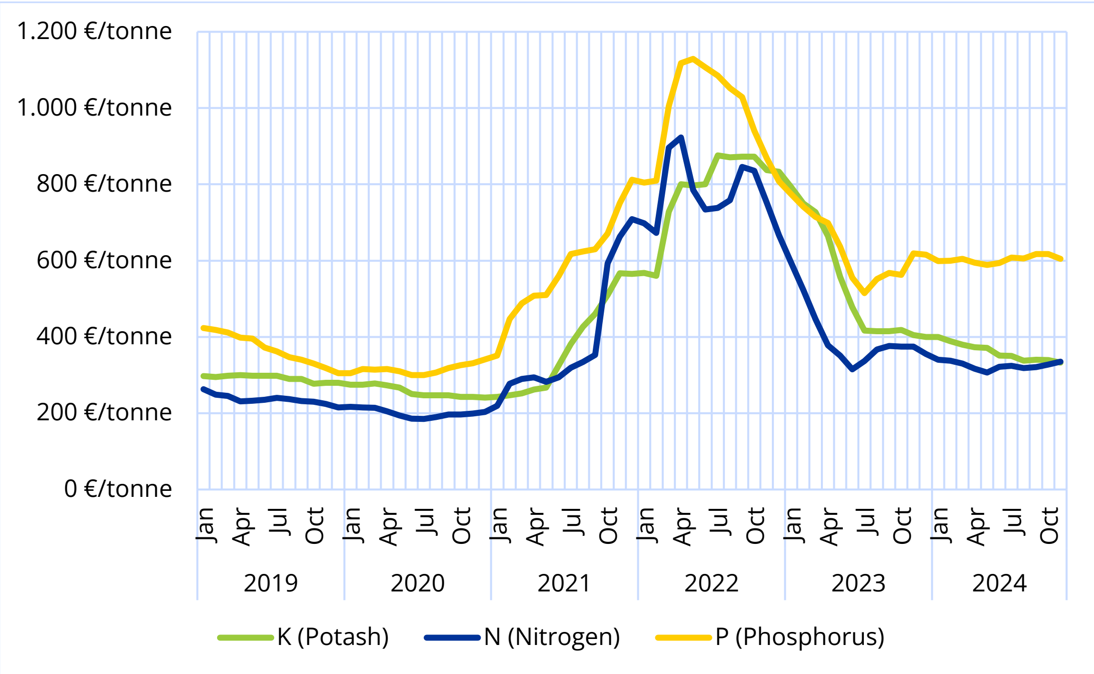

Figure 3: Prices of mineral fertiliser 2019-2024 (EC DG AGRI 2024).

### *3.3.4.3 Indicator:*

The indicator considers appropriate prices for demand and supply on the basis of current (expected) prices for fertilisers such as RDF. The price of RDF plays a crucial role in determining whether they become a viable, sustainable alternative to mineral ones while reflecting also ecological and social external effects.

### *3.3.4.4 Geographical scope:*

The geographical scope of RDF prices is influenced by local, regional, and international factors such as infrastructure, energy prices, demand-supply dynamics, and government policies. Prices can vary dramatically based on where the RDF is produced and used. Those prices will have to be competitive with global markets. Nevertheless, it is noteworthy that from 2026 on imported fertilisers are subject to the EU's Carbon Border Adjustment Mechanism (CBAM; (European Union 2023; Annex I), which means that importers of mineral fertilisers will have to buy and surrender CBAM certificates corresponding to the quantity of embedded GHG-emissions in the fertilisers (EC DG TAXUD - European Commission - Directorate-General for Taxation and Customs Union 2023). This might lead to a price increase for mineral fertilisers.

### *3.3.4.5 How to measure:*

Two different approaches can help measure the indicator. One the one hand, statistical analysis of current prices and future price projections. For this a collection and analyses of historical price data for mineral and RDF over time allows to identify trends and calculate medium prices. This can help compare current RDF prices and conventional fertilisers to gauge competitiveness.

The second, additional approach is the Price Sensitivity Meter (PSM) according to Peter van Westendorp (Moshkin et al. 2023). This method allows to determine price acceptance and willingness of the potential RDF buyers. It derives at price points at which they perceive the product as too cheap, too expensive, and acceptable. Here, survey results from the predecessor INTERREG VI B North-West Europe project "ReNu2Farm: Nutrient–Recycling – from pilot production to farms and fields" can help define the price acceptance rating levels. Additionally, the results from Moshkin et al. (2023) can be used.

### *3.3.4.6 Measurement:*

Costs and prices have to be quantified in monetary terms e.g., the national currency of the countries which is euros. To compare costs and prices in different areas also Purchasing Power Parities might be used.

In the context of traditional mineral fertiliser production cost include cost for raw materials (natural gas, phosphate rocks), energy, labour, capital investments and transportation. They depend on the scale of production, the technology used and the efficiency of the process. However, RDF can be seen as a by-product (e.g., sewage sludge or organic food waste), if they are produced as a secondary product from waste processing (e.g., in the case of struvite). Yet, if the primary goal / main purpose is not waste processing but to produce fertilisers from waste materials, then these fertilisers may rather be considered as primary products.

If production costs for RDF are calculated as for by-products this might lead to lower production cost, because the raw materials are cheaper. Moreover, the energy and labour cost need to be allocated between the service/ product of waste processing and the product RDF. Nevertheless, additional initial investments as well as operational expenses might be needed to produce RDF as a by-product. In our analysis, recycling-derived fertilisers (RDFs) such as ammonium sulphate are generally treated as by-products, and we include only the additional production effort (e.g., energy, processing chemicals) in the assessment, while excluding costs associated with the underlying waste treatment process. However, we acknowledge that ammonium sulphate is not always a by-product — depending on the technology used, it may be produced through a dedicated recovery process. In such cases, system boundaries and environmental burdens may shift, and these differences are considered in the sensitivity analysis or scenario design.

On the other side, market acceptance and market conditions (competition with synthetic fertilisers) need to be reflected. Moshkin et al. (2023: 8) show that the best possible market coverage for RDF ('total reach') can be ensured if the prices of RDF are 30-46% below the price of mineral fertilisers (prices per kilogram of nutrients as the reference fertiliser).

### *3.3.4.7 Rating levels:*

To evaluate the appropriate prices for demand and supply, following terms are used for calculation: Production costs (p), Willingness to pay/acceptance to pay (a), profit margin (x), and conventional fertiliser price (c).

*Table 15: Five-level rating system for appropriate prices for demand and supply*

| Rating Level | Rating Category | Explanation |
|---|---|---|
| Level 1 | High acceptance: $p + x < a < c$ | Farmers are willing to pay a price that is significantly above production costs and below conventional fertiliser prices.<br>In other words: price to maximize total reach/ market coverage is higher than direct production cost. |

| | | |
|---|---|---|
| Level 2 | Acceptance at parity: $p + x < a = c$ | The willingness to pay aligns with the price of conventional fertilisers. This indicates a competitive market but may limit profit margins.<br>In other words: price is roughly the same as for the reference fertiliser and higher than direct production cost |
| Level 3 | Neutral acceptance: $p \leq a \leq c$ | Production costs are within the acceptable range to conventional fertiliser prices but at the lower end. The market is stable but does not indicate high demand or profit margins.<br>In other words: price is roughly the same as for the reference fertiliser and as high as direct production cost |
| Level 4 | Limited acceptance: $p > a < c$ | Farmers perceive RDF as more expensive than they are willing to pay, but conventional prices are lower. This may indicate potential issues with market penetration or value perception. |
| Level 5 | Low acceptance: $p > c$ | RDF is priced above conventional fertilisers, leading to low demand. This scenario suggests a significant barrier to market entry or acceptance. |

*Reference: Own table*

### 3.3.5 Criterion (9): Share of imports

#### *3.3.5.1 Challenge and Criterion:*

The global challenge focuses on imbalances in global trade, dependencies, and underdevelopment; it leads to global foreign trade balance, self-sufficiency, and the reduction of dependencies in traditional mineral resources. Usually, the criterion share of import is used to evaluate trade-dependencies for products. Economic dependence, for example on imported fertilisers in agriculture, can pose a risk to long-term supply security. Similar to the energy sector, the costs of these imports must be covered by the income of European farmers and households. This reduces domestic purchasing power and requires Europe to generate trade surpluses in other sectors to offset the import expenditures.

The EU depends on importing most of the mineral fertilisers.

Fehler! Verweisquelle konnte nicht gefunden werden. highlights the net imports for fertilisers between 2005 and 2017.

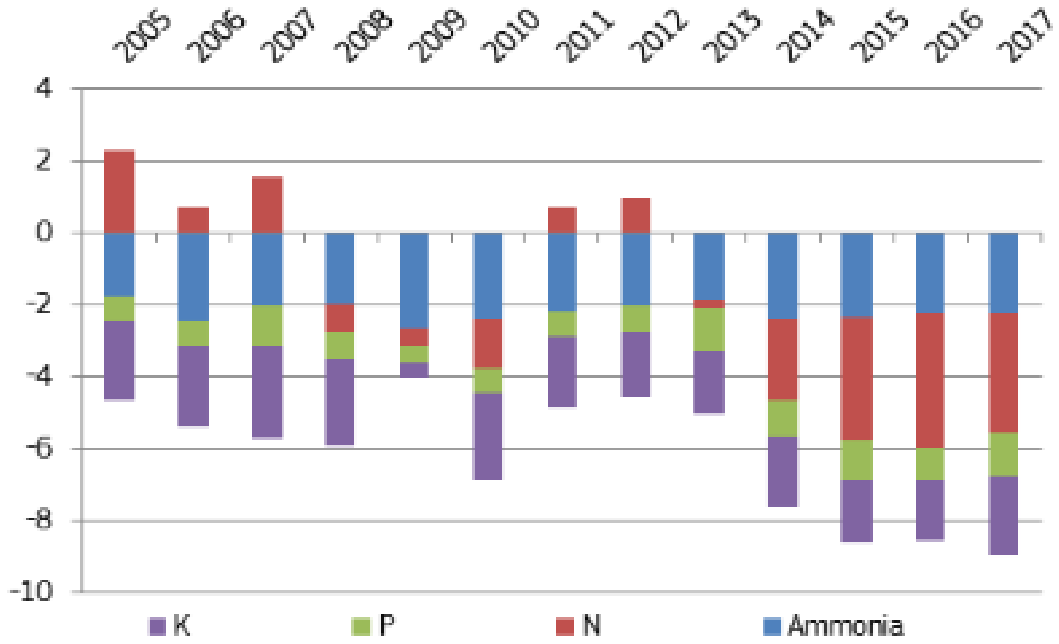


Figure 4: EU net trade for ammonia, nitrogen, potassium and phosphate (EC DG AGRI 2019: 3)

### 3.3.5.2 Focus SDG:

As a criterion for the objective of reducing external economic dependence, the import share of fertilisers is considered. This criterion can be linked to SDG 17 Partnerships for the Goals, highlighting the importance of resilient and fair international supply chains, thus emphasizing the importance of global cooperation and partnership in addressing the complex issues of trade imbalances and the dependencies that limit sustainable development.

### 3.3.5.3 Indicator:

The adopted indicator measures share of imports for fertilisers into the EU. If the chosen agricultural practice or fertilisation strategy relies heavily on fertilisers or input materials that are largely imported and for which no domestic alternatives are available, this leads to significant external dependency. In extreme cases, the EU might be forced to make political compromises to secure continued access to these materials. This risk can be mitigated through strategies that promote independence and substitutability, e.g., through domestic recycling of nutrients, organic fertilisers, or increased efficiency in fertiliser use.

### 3.3.5.4 Geographical scope:

The objectives of the EU's Common Agricultural Policy, including and focusing on the operation and development of the internal market for agricultural products (TFEU: Art. 38) lead to a broader geographical scope for this criterion. Therefore, the share of imports for fertilisers for the EU will be used.

### 3.3.5.5 Rating levels

For the objective of low external economic dependence, the import share of fertilisers is used as a criterion. If multiple fertiliser types are used, the overall import share is calculated as a weighted average based on their usage. The criterion is operationalised in five levels.

### 3.3.5.6 How to measure:

One approach is to conduct desk research for secondary data on the share of imports for conventional mineral fertilisers and RDF in the EU. Regarding current trade data, the data availability is limited. AGRIDATA publishes data on the fertilisers production, imports and exports. (EC DG AGRI 2025a; 2025b). To estimate the import share of fertilisers, available data on domestic production, imports, and exports are used. Although information on stock changes is not available, a simplified approach can still provide a reasonable approximation. The import share is calculated as the ratio of net imports (imports minus exports) to the total apparent supply (domestic production plus net imports). This method does not account for year-to-year changes in storage volumes but allows for a practical and consistent estimation of import dependence based on available statistics. It should be noted, however, that domestic production itself often relies on imported raw materials or intermediate goods (e.g., natural gas for nitrogen fertilisers). This means that the actual import dependency may be underestimated, as indirect dependencies through upstream supply chains are not captured by this simplified approach.

### 3.3.5.7 Example

A first analysis of the import shares for fertiliser product groups was conducted. It is noteworthy that this analysis only looks at final fertiliser products and does not include upstream intermediate goods such as raw materials or precursor chemicals. As such, the figures may underestimate the overall import dependency, especially for domestically produced fertilisers that rely on imported inputs. Nevertheless, the analysis provides a useful first indication of the direct import share associated with key fertiliser categories.

*Table 16: Import Shares and Rating Levels for Final Fertiliser Products (Excluding Intermediates), 2022–2023[3]*

| Product group | 2023 | 2022 | Rating level |
|---|---|---|---|
| Ammonia | 13,35% | 14,88% | 2 |
| Nitrogenous fertilisers | 16,61% | 18,22% | 2 |

[3] Note: A negative import share may result from high export volumes relative to imports and domestic production.

| | | | |
|---|---|---|---|
| Phosphates | 28,94% | 28,12% | 3 |
| Phosphatic fertilisers | 5,41% | -4,06% | 1 |
| Potassic fertilisers | 30,97% | 21,91% | 4 |

*Reference: Own table. Data from EC DG AGRI 2025a; 2025b*

#### 3.3.5.8 Synergies:

This criterion has an interlinkage with criterion 14 (conflict avoidance). While both indicators address aspects of supply security, they capture different dimensions of dependency. The import share reflects the overall economic reliance on foreign fertiliser sources, whereas the conflict risk indicator assesses the geopolitical vulnerability of imports based on their origin and associated stability risks. Together, they offer a complementary perspective: high import shares become particularly critical when concentrated in politically unstable supplier countries.

### 3.3.6 Criterion (10): Market Infrastructure Readiness

#### 3.3.6.1 Challenge and Criterion:

The global challenge addresses public debt and the inadequate endowment of merit goods which would lead to inadequate infrastructure. Rogall (2012: chapter 13-14) names adequate investments into infrastructure as a goal for resource- and agricultural policies. Unfortunately, at the point of his research in 2012 the network did not define a specific objective for agricultural policies for this challenge.

The consortium of ReNu2cycle decided to focus on the criterion of market infrastructure as comparable to merit goods.

#### 3.3.6.2 Focus SDG:

Whereas the challenge of public debt is closely related to SGD 8 and SDG 17, the criterion of market infrastructure is rather related to SDG 12 Responsible Consumption and Production. SDG 12 wants to "achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment" (UN Stats 2024).

#### 3.3.6.3 Indicator:

The indicator Market Infrastructure Readiness evaluates various characteristics of market infrastructure for each RDF category. These characteristics include distribution networks and channels (including retail), available product variations (such as size, brands, formulation, and blends), established regulations, standards, certification and labelling, and low market entry barriers.

### 3.3.6.4 Geographical scope:

The geographical scope regarding mineral fertilisers and RDF market infrastructure can vary widely depending on the region, the specific supply chain dynamics, and the policy frameworks in place. However, the way RDF are produced, traded, and utilized can span multiple geographical areas, with specific implications for local, regional, and international levels. For the purpose of the analysis and based on the legal definition (Commission notice on the definition of relevant market for the purposes of Community competition law 1997) the consortium defines: The relevant geographic market comprises the area in which the undertakings concerned are involved in the supply and demand of products, in which the conditions of applying the products are sufficiently homogeneous.

### 3.3.6.5 How to measure:

An expert team should evaluate the market infrastructure and the aforementioned characteristics for each region. Information could be gathered through desktop research, interviews, stakeholder dialogues, living labs, and field trials.

### 3.3.6.6 Rating levels:

This criterion refers to how established and robust the market, regulations, infrastructure, and product offerings are for each fertiliser type. It reflects the extent to which the product is widely accepted and integrated into farming practices.

*Table 17: Five-level rating levels for Market infrastructure readiness*

| Rating Level | Explanation |
|---|---|
| Level 1 | Fully Developed: The market is mature, with well-established regulations, broad market acceptance, and strong infrastructure. The product is widely used and trusted by farmers and highly integrated into agricultural practices. |
| Level 2 | Well-Developed, Some Gaps: The market is growing, with established infrastructure and increasing adoption. However, there are some gaps in certain regions or sectors, and the product may not yet be as widely used or trusted in all areas. |
| Level 3 | Emerging, developing: The market is still in the early stages of development. Adoption and awareness are growing, but challenges exist in terms of widespread use, regulation, and acceptance. There may be inconsistent demand and limited infrastructure. |
| Level 4 | Inconsistent, Limited: The market is inconsistent and fragile, with low adoption in many regions. There may be few regulations or standards, and the product is largely viewed as a niche offering or alternative. |

| | |
|---|---|
| Level 5 | Underdeveloped, Dependent on External Sources: The market is non-existent or highly underdeveloped, with minimal adoption and no formal regulatory framework. The product is either new or experimental, with limited visibility and low acceptance. |

*Reference: Own table*

## 3.4 Development of Evaluation Criteria for Assessment of the Socio-Cultural Dimension

### 3.4.1 Overview

#### *3.4.1.1 Challenges and goals*

The challenges in the socio-cultural dimension result in five overarching goals. The main global challenges relate to erroneous trends in the economy, politics, society, an inequality of opportunities, unequal distribution of income and wealth, and potential technological risks. Potential threats are social insecurity, poverty, demographic change as well as violent conflicts, and internal and external insecurity. Goals can be derived from these challenges to overcome them. Representative criteria and indicators were selected for each of these objectives, which can be used to assess the contribution that a supply option can be expected to make to achieving the objectives. Table 18 summarises these criteria and indicators of the social-cultural dimension. They are then explained in turn in detail.

*Table 18: Overview of the social-cultural dimension with criterion, Focus SDG and indicator*

| Economic Dimension | | | |
|---|---|---|---|
| No. | Criterion (to respond to global challenge) | Focus SDG | Indicator |
| 11) | Establish good governance for acceptance and awareness for RDF uptake | SDG 16: Peace, justice and strong institutions | RDF Acceptance and Awareness |
| 12) | Avoidance of poverty and dependencies | SDG 10: Reduced inequalities | Dependence of farmers on others |
| 13) | Equal opportunities uptake & Market availability and uptake | SDG 16: Peace, justice and strong institutions<br>SDG 10: Reduced inequalities | Targeted types of stakeholders involved in the value chain (decentralized, democratic) |

| | | | |
|---|---|---|---|
| 14) | Geostrategic independency (EU) | SDG 17: Partnerships for the goals | Conflict potential of the resources used |
| 15) | Abandonment of technologies with significant risks | SDG 09: Industry, Innovation and Infrastructure | Technology Risk |

*Reference: Own table*

### 3.4.2 Criterion (11): Acceptance and awareness for RDF uptake

#### *3.4.2.1 Challenge and Criterion:*

Acceptance and awareness are crucial for establishing good governance in the fertiliser market for several reasons. The INTERREG NWE project ReNu2Farm has investigated the farming community's awareness and acceptance of RDF. Through a survey of over 1,200 farmers in NWE, they found that the term RDF was not widely recognized among farmers and depending on input sources of the RDF, a lower awareness and acceptance has been detected.

#### *3.4.2.2 Focus SDG:*

The criterion links to the SDG 16 Peace, Justice, and Strong Institutions. The relationship between SDG 16 and good governance for RDF awareness and acceptance lies mainly in fostering stability and trust to manage resources sustainably and reduce potential conflicts. RDF awareness and acceptance through the promotion of RDF characteristic reduce misconceptions.

#### *3.4.2.3 How to measure:*

Measuring Indicators for RDF awareness and acceptance needs a mixed methods approach.

Firstly, interviews will take place through the Living Lab events with stakeholders alongside the RDF value chain. Additionally, a survey on awareness and acceptance can be used with closed questions for a quantitative analysis.

#### *3.4.2.4 Data Availability:*

Data is gathered through the LLA in the project ReNu2Cycle as well as surveys. Some data are already available from the previous ReNu2Farm project.

#### *3.4.2.5 Geographical Scope:*

The geographical scope of the analysis will cover NWE, which serves as the largest territorial unit for the assessment. The focus will be on regional contexts where data availability and relevance allow for meaningful analysis. Given the heterogeneity in agricultural practices and sustainability metrics across regions, the assessment will in general not account for regional variations but rather refer to overarching characteristics of participating NWE regions. To reflect local realities, follow up research is needed.

#### 3.4.2.6 Measurement

The team expects the survey to cover several questions. A metric/ tool for rating the acceptance such as a Likert scale will be used.

#### 3.4.2.7 Rating levels:

*Table 19: Explanation of rating levels for criterion (11): acceptance and awareness for RDF uptake*

| Rating Level | Explanation |
|---|---|
| Level 1 | High acceptance of RDF |
| Level 2 | Acceptance can be achieved through more communication, few critics |
| Level 3 | Equal positive and negative response |
| Level 4 | More negative than positive response |
| Level 5 | No acceptance of RDF at all |

*Reference: Own table*

### 3.4.3 Criterion (12): Dependence of farmers on others

#### 3.4.3.1 Challenge and Criterion:

The global challenge aims at the avoidance of poverty and dependencies. For farmers the risk of poverty is higher if they are dependent on others, e.g., financial partners or monopolists for fertilisers or seeds. Therefore, the adopted indicator captures the impact on dependence of farmers on others beyond the RDF supply and its application. As such, it covers equipment, workforce etc. By promoting RDF, farmers' dependency shifts from global suppliers to local producers, equipment providers, and knowledge-sharing networks, broadening their economic interdependencies.

#### 3.4.3.2 Focus SDG:

The global goals it usually links to is SDG 1 No Poverty and SDG 10 Reduced inequalities. For the purpose of the sustainability Assessment of Fertilisers the indicator had to be adapted so that it is only loosely linked to SDG 10 as the dependence of farmers on others beyond the RDF supply and its application can cause inequal market positions.

### 3.4.3.3 Indicator:

Dependency of farmers on the fertiliser value chain (beyond supply) is a qualitative indicator. This indicator assesses the degree of the dependence farmers have on external actors (e.g., suppliers, financial institutions, large monopolistic companies) for the purchase of fertilisers, seeds, or other agricultural inputs.

This indicator assesses how the adoption of RDF affects farmers' economic independence by considering several dimensions of dependence and autonomy. While RDF can reduce dependency on multinational suppliers, they may also introduce new dependencies on local RDF producers, specialized equipment, skilled labour, and technical expertise. The goal is to capture the net effect of RDF adoption on farmer resilience and poverty risk.

The following aspects influence the dependency:

- Reduced dependency on traditional suppliers: With RDF supply, farmers rely less on multinational fertiliser producers, diversifying their input sources.
- Dependency on local RDF producers: Farmers may develop stronger ties with local waste management and RDF producers for fertiliser supply, fostering regional economic collaboration.
- Equipment dependency: New RDF types may require specific application equipment, increasing reliance on manufacturers and suppliers of these technologies.
- Workforce needs: Farmers might depend on skilled labour for managing RDF application processes and integrating them into their existing practices.
- Knowledge transfer: Adoption of RDF increases reliance on training and advisory services, as farmers need expertise in handling and applying new fertiliser types effectively.

### 3.4.3.4 Geographical scope:

The geographical scope of the analysis will cover NWE, which will serve as the largest territorial unit for the assessment. The focus will be on regional contexts where data availability and relevance allow for meaningful analysis. Given the heterogeneity in agricultural practices and sustainability metrics across regions, the assessment will in general account not for regional variations but rather refer to overarching characteristics of participating NWE project regions. To reflect local realities, follow up research is needed.

### 3.4.3.5 How to measure:

Data is gathered through surveys and the LLA in the project ReNu2Cycle. The consortium is aware that participation in additional survey might be low. In this case expert knowledge from the living lab will be considered to derive ratings.

### 3.4.3.6 Example

A short example demonstrates the application of the Rating Levels to RDF Adoption: When considering the adoption of RDF, the key challenge is finding a balance between reducing dependency on multinational fertiliser producers and increasing reliance on local producers, specialized equipment, and skilled labour. Ideally, RDF adoption can help diversify input sources and increase local resilience, but these benefits depend on regional infrastructure, knowledge transfer systems, and labour markets.

For example, if RDF are locally produced and farmers can apply them using existing equipment, the dependence on external actors will be low. However, if the application of RDF requires new technology or specialized labour that is not readily available, farmers may become dependent on external suppliers for both equipment and expertise, increasing their vulnerability.

### 3.4.3.7 Rating levels:

To evaluate the net effect of fertiliser adoption on farmer independence and economic resilience the team will consider both the positive impacts (such as local sourcing and regional collaboration) and negative impacts (such as dependence on specialized equipment and external knowledge providers). Table 20 gives a qualitative description of the rating levels.

*Table 20: Explanation of rating levels for criterion (12): dependence of farmers on others*

| Rating | Category | Explanation |
|---|---|---|
| 1 | High Independence, Low Dependency | Farmers have minimal dependence on external suppliers, equipment, or knowledge providers. They can source fertilisers locally and apply them using existing equipment with little need for external expertise. Self-sufficiency is high, and economic resilience is strong. Local production is widespread, and farmers have access to diverse sources of information and support. |
| 2 | Moderate Independence, Limited Dependency | Farmers have some reliance on local RDF producers and may need specific equipment for RDF application. However, there is still some autonomy in sourcing RDF and applying them using existing technologies. Training and technical support are available but not necessarily universally. The market for RDF is growing, and dependence on external knowledge and labour is moderate. |
| 3 | Moderate Dependency, Vulnerable to External Factors | Farmers are moderately dependent on producers for supply and may need specialized equipment for application. There is an increasing reliance on external advisors, skilled labour, and training to apply fertilisers effectively. Farmers are at risk of |

| | | |
|---|---|---|
| | | increased costs due to specialized equipment or labour needs. Suppliers may have limited capacity, and market fluctuations may affect availability. |
| 4 | High Dependency, Limited Alternatives | Farmers are heavily dependent on producers for supply and may face challenges in sourcing fertilisers if supply chains are disrupted. They rely on specialized equipment for application and may have limited access to affordable labour or training. Farmers have few alternatives for fertilisers, which increases their vulnerability to price fluctuations, monopoly control, or local supply shortages. |
| 5 | Complete Dependency, At Risk of Exploitation | Farmers are completely dependent on a single supplier or external actors for all aspects of production, application, and technical support. They have no control over the price or availability of fertilisers and are highly reliant on external financing or high-interest loans to acquire necessary equipment or hire skilled labour. The lack of alternatives leaves farmers at high risk of economic exploitation, poverty, and financial instability. |

*Reference: Own table*

### 3.4.4 Criterion (13): Targeted types of stakeholders: (decentralised, democratic) value chain

#### *3.4.4.1 Challenge and criterion*

The global challenge addresses inequal opportunities, unequal distribution of income and wealth. Equal opportunities and distributive justice can be achieved when value creation networks are plural and all groups can represent their interests. It is important that the decision is not dictated by the economically strongest partner, but that common participatory decision-making structures exist. The following aspects promote inclusiveness and democratic decision-making and equal opportunities:

- The number of stakeholders in decision-making. Stakeholders typically include governments, farmers, industry representatives, environmental groups, scientists, and international organisations. An inclusive governance model may require collaboration among all or most entities within the RDF supply–demand value chains, depending on the specific supply geographical chains (local, national, or global).
- Mechanism of participation are democratic mechanisms, such as public consultations, stakeholder forums, and participatory decision-making workshops, ensuring diverse perspectives.

- Market concentration of suppliers: fertiliser markets are often dominated by a few large multinational corporations, leading to high market concentration. This can limit competition and influence the cost and availability of both traditional and recycled fertilisers. Introducing RDF into the market could reduce concentration by creating opportunities for smaller, local producers using waste streams.
- Economic dependency among stakeholders is generally seen between end-users and producers for their customer base. Regarding the value chain, dependencies also extend to raw materials supply and trade entities for RDF. The interdependency of RDF value chain stakeholders requires balanced governance to align interests.

#### *3.4.4.2 Focus SDG:*

The criterion links to the SDG 16 Peace, Justice, and Strong Institutions. As well as SDG 10 Reduced inequalities. By engaging a decentralised and democratic value chain, Future fertilisers foster inclusive decision-making and transparent governance structures, contributing to SDG 16. Targeting diverse stakeholder groups across the value chain helps reduce systemic inequalities and supports the empowerment of marginalized actors, aligning with SDG 10.

#### *3.4.4.3 How to measure:*

This indicator cannot be captured directly. To evaluate the indicator expert field knowledge from field case studies is needed. The evaluation is than only valid for the specific field trial/ living lab.

A kind of checklist approach is used to evaluate the indicator. The more characteristics are met, the better the evaluation of the specific fertiliser:

- Number of stakeholders involved in decision-making about the value chain: This characteristic can be considered fulfilled if there are three or more direct stakeholders involved.
- Different groups are involved in governance and decision-making within the RDF supply chain. This includes at least three of the following: governments, farmers, industry representatives, environmental groups, scientists, and international organisations.
- Mechanism of participation (democratic): The quality of participation mechanisms, such as public consultations, stakeholder forums, workshops, and voting systems, ensure that diverse perspectives are included in the decision-making process.
- Democratic decision making: voting and decision-making rights are not based on financial contributions, market dominance or lobbying power. Rather decision making emphasizes equal representation, e.g., applying one stakeholder one vote or weighted voting based on different criteria. Also, a consensus-based model might be possible.

- Participatory budgeting or resource allocation: In some governance models, resources (whether financial, technological, or regulatory) are distributed based on participation and needs rather than financial contribution. For example, subsidies for RDF production or research funding could be allocated based on the potential impact for sustainable agriculture, rather than based on market power or economic strength.

#### *3.4.4.4 Data Availability:*

Data is gathered through the LLA in the ReNu2Cycle project. The experts from the consortium should be able to make statements about whether the above criteria/characteristics are met. In addition, interviews or workshops can provide more clarity on the above questions.

#### *3.4.4.5 Geographical Scope:*

The geographical scope of the analysis will cover NWE, which serve as the largest territorial unit for the assessment. The focus will be on regional contexts where data availability and relevance allow for meaningful analysis. Given the heterogeneity in agricultural practices and sustainability metrics across regions, the assessment will in general not account for regional variations but rather refer to overarching characteristics of participating NWE regions. To reflect local realities, follow up research is needed.

#### *3.4.4.6 Measurement units:*

For this indicator, the number of fulfilled checklist criteria is counted: minimum number of stakeholders in decision-making, different groups of stakeholders involved, mechanism of democratic participation, democratic decision making, participatory resource allocation.

#### *3.4.4.7 Rating levels:*

*Table 21: Explanation of rating levels for criterion (13): targeted types of stakeholders: (decentralised, democratic) value chain*

| Rating | Explanation |
|---|---|
| 1 | At least four checklist-criteria are usually fulfilled in value creation network of this specific RDF/ fertiliser/ project. |
| 2 | At least three checklist-criteria are usually fulfilled in value creation network of this specific RDF/ fertiliser/ project |
| 3 | At least two checklist-criteria are usually fulfilled in value creation network of this specific RDF/ fertiliser/ project |
| 4 | At least one checklist-criteria are usually fulfilled in value creation network of this specific RDF/ fertiliser/ project |

| | |
|---|---|
| 5 | None of the checklist-criteria is usually fulfilled in value creation network of this specific RDF/ fertiliser/ project |

*Reference: Own table*

## 3.4.5 Criterion (14): Conflict potential of the resources used

### *3.4.5.1 Challenge and Criterion:*

The global challenge addresses internal and external insecurity through violent conflicts with an EU geostrategic independence from third-countries. RDF are an innovative solution for reducing reliance on traditional, often geopolitically sensitive, resources of raw materials that are used in mineral fertiliser. The criterion aims to considers the conflict potential of these resources used.

### *3.4.5.2 Focus SDG:*

The use of RDF instead of mineral fertilisers and their widespread adoption can bring a series of geopolitical, economic, and social considerations that intersect with one another. The SDG 17 Partnerships for the goals emphasizes the importance of global cooperation and partnership in addressing the complex issues.

### *3.4.5.3 Indicator:*

The conflict potential of fertilisers is essentially influenced by the concentration of the countries of origin from which the fertiliser source is imported (three-country concentration of imports: 3CCI) and their weighted risk of conflict. The import quantities per country and product are shown in the official foreign trade statistics. A country's risk of conflict can be compared using the indicator 'political stability and no violence' of the Worldwide Governance Indicators (Kaufmann et al. 2020).

The proportion of the three countries of origin with the largest import quantities of the fertiliser source in Europe (3CCI) is used as a measure of the concentration. The weighted conflict risk (WCR) of the individual fertiliser sources is based on the proportional import quantities and the WGI conflict risk of the individual countries.

### *3.4.5.4 Geographical scope:*

The geographical scope of the analysis will cover the EU, because the consortium expects data availability of imports on an aggregated level of the EU to be most valid.

### *3.4.5.5 How to measure:*

For conventional fertilisers the data on imports can be derived from EC DG AGRI (2025b). Data on government indicators are available at WBG (2024). Both sub-indicators (three-country import concentration and weighted conflict risk) have to be calculated.

Fehler! Verweisquelle konnte nicht gefunden werden. shows the results of some typical conventional fertilisers based on EC DG AGRI-data from 2023. In the context of conventional fertilisers, trade statistics (e.g. EC DG AGRI 2025b) can be used. For new fertilisers, such as RDF, own calculations from the Living Lab can be used. A locally produced RDF will usually have a low import concentration as well as a low weighted conflict risk.

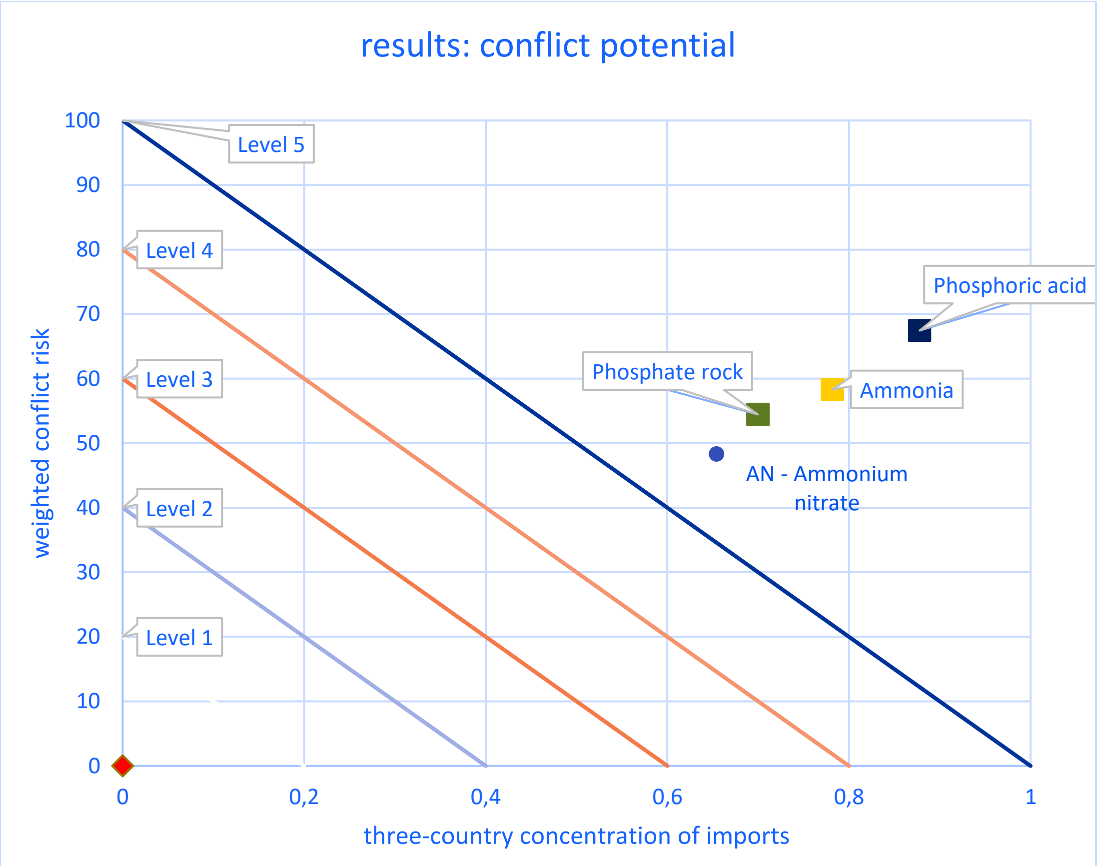


Figure 5: Results for the indicator conflict potential (examples)

#### *3.4.5.6 Rating levels:*

*Table 22: Explanation of rating levels for criterion (13): conflict potential of the resources used*

| Rating | Explanation |
|---|---|
| 1 | Fertilisers below the threshold that moves from less than 40% WCR to less than 40% 3CCI. |
| 2 | Fertilisers below the threshold that moves from less than 60% WCR to less than 60% 3CCI, however above threshold for level 1. |

| | |
|---|---|
| 3 | Fertilisers below the threshold that moves from less than 80% WCR to less than 80% 3CCI, however above threshold for level 1. |
| 4 | Fertilisers below the threshold that moves from less than 100% WCR to less than 100% 3CCI, however above threshold for level 1. |
| 5 | Fertilisers above the threshold that moves from less than 100% WCR to less than 100% 3CCI, worst performer. |

*Reference: Own table*

#### 3.4.5.7 Synergies:

This indicator has synergies with indicator 9 (import share).[4]

### 3.4.6 Criterion (15): Abandonment of technologies with significant risks

#### 3.4.6.1 Challenge and Criterion:

The challenge surrounds technologies with significant risks and the respective abandonment. Fertilisers themselves can be understood as a technology: they are intentionally developed products designed to improve plant growth by delivering essential nutrients to crops. Their production, composition, mode of action, and application methods often rely on scientific and technological innovation. The application of new technologies can bring improvements to or simplifications of people's daily lives and increase efficiency. However, there can also be dangers to people and nature. Technological risk assessment is a common criterion und quality and sustainability management. It is noteworthy that even some high developed technologies might pose very high technological risk e.g., nuclear power.

#### 3.4.6.2 Focus SDG:

The challenge surrounding technologies with significant risks RDF is connected to SDG 16: Peace, Justice, and Strong Institutions as well as SDG 09: Innovation and Infrastructure.

#### 3.4.6.3 Indicator:

This indicator assesses the potential risks associated with the use of specific technologies in the production, application, or lifecycle of fertilisers. It considers the maturity of the technology (e.g., proven vs. experimental), the dependency on complex or sensitive processes, and the likelihood of failure or disruption in real-world farming conditions.

Some fertiliser technologies pose risks even during normal operation—beyond their environmental impacts such as emissions or nutrient runoff. For example, certain fertilisers may involve hazardous substances, complex handling procedures, or by-products that

[4] For an explanation of the distinction see Criterion (9): Share of imports, page 41.

require special disposal. In addition to these normal operation risks, some fertiliser systems carry increased danger in case of accidents, misapplication, or external disturbances (e.g., extreme weather or system failure). In risk analysis, a risk is defined as “a function of the probability of an adverse health effect and the severity of that effect, consequent to a hazard” (REGULATION (EC) No 178/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 28 January2002 laying down the general principles and requirements of food law, establishing the European Food Safety Authority and laying down procedures in matters of food safety 2022). Accordingly, technological risk can be assessed based on the expected likelihood of damage and the potential severity, typically represented in a risk matrix (Pfeufer 2014).

The adopted indicator is the Technology Risk, assessed by a Risk matrix, which helps identify which risks require immediate attention, which ones need mitigation planning, and which ones can be accepted. A further concretisation of the technological risk assessment methodology will follow, specifying which types of risk are included in the indicator framework. This will build on the broad spectrum of potential risks associated with recycling-derived fertilisers (RDFs), including: financial risks to farmers (e.g., investment in new machinery), technological failure risks, contamination risks from heavy metals, pathogens, and organic pollutants, as well as challenges related to input material variability, nutrient recovery efficiency, leaching, and soil microbiome impacts. Broader systemic risks such as air pollution, farmer and consumer acceptance, infrastructure and operational costs, regulatory compliance, and the lack of standardised labelling and certification will also be considered for their relevance. This clarification will enable targeted application of the Technology Risk Indicator in the subsequent assessment phases.

#### *3.4.6.4 Geographical scope:*

The geographical scope of the analysis will cover NWE, which serves as the largest territorial unit for the assessment. The focus will be on regional contexts where data availability and relevance allow for meaningful analysis. Given the heterogeneity in agricultural practices and sustainability metrics across regions, the assessment will in general account not for regional variations but rather refer to overarching characteristics of participating NWE regions. To reflect local realities, follow up research is needed.

#### *3.4.6.5 How to measure:*

To measure the technological risk a Risk matrix will be used. To assess the technological risk of fertiliser technologies in a matrix, two key dimensions are considered: the severity of damage and the probability of occurrence. These are evaluated in three levels each, following the project methodology.

*Table 23: Classification of Damage Severity*

| Level | Description |
|---|---|
| 1 | Negligible: Hardly any impact on human health or ecosystems, in both normal operation and in case of failure. |
| 2 | Critical: Significant negative effects on human health or ecosystems in the event of a malfunction or failure. |
| 3 | Catastrophic: Lethal effects on human health or ecosystems in the event of a failure; long-term negative effects on health during normal operation. |

*Reference: Own table*

*Table 24: Classification of Probability of Damage*

| Level | Description |
|---|---|
| 1 | Unlikely: A well-established and proven technology is used. |
| 2 | Rare: For established technologies, there is scientific evidence suggesting potential harm during normal operation, though not yet conclusive. Or: the technology is not yet mature, and unknown effects during normal use cannot be excluded. |
| 3 | Likely: Incidents or known harmful effects during normal use have already occurred with this technology. |

*Reference: Own table*

From the combination of these two factors—expected damage and damage probability—a risk matrix can be derived to assess the overall technological risk of a given fertiliser.

*Table 25: Rik matrix*

| | | Probability of risk exposure | | | |
|---|---|---|---|---|---|
| | | Very low | Low | Medium | High |
| Possible severity of damage | Mild injuries or illnesses | 1 | 1 | 2 | 3 |
| | Moderate injuries or illnesses | 1 | 2 | 3 | 4 |
| | Serious injuries or illnesses | 2 | 3 | 4 | 5 |
| | Possible death, catastrophe | 3 | 4 | 5 | 5 |

*Reference: Own table*

### 3.4.6.6 Rating levels:

The 5-Level rating-scale for risks as defined by Nohl with their danger level

*Table 26: Explanation of rating levels for criterion (15): abandonment of technologies with significant risks*

| Rating No. | Rating | Explanation |
|---|---|---|
| 1 | None | The risk is negligible or non-existent. There is no significant impact on RDF quality, safety, or adoption. No mitigation is required. |
| 2 | Mild | The risk has minimal impact and is easily managed. Any negative effects are small and do not significantly affect RDF functionality or safety. Minor adjustments may be needed. |
| 3 | Moderate | The risk has a noticeable impact but does not pose an immediate threat. If unmanaged, it could cause some operational, environmental, or financial issues. Requires monitoring and mitigation strategies. |
| 4 | Serious | The risk is significant and requires immediate attention. It can cause major disruptions in RDF production, safety concerns, or regulatory compliance issues. Strict mitigation measures are needed. |
| 5 | Catastrophical | The risk poses a severe and potentially irreversible threat. It could lead to serious environmental damage, human health hazards, or the failure of RDF adoption. Urgent and large-scale intervention is required. |

*Reference: Own table*

# 4 Visual communication of SA-4F results

As part of the ReNu2Cycle project, a multi-criteria sustainability assessment will be conducted to evaluate RDF and their contributions to sustainability in NEW compared to conventional mineral fertilisers. The aim is to provide key stakeholders—such as farmers, policymakers, resource and technology providers, and market players—with targeted visualizations and insights into the sustainability impacts of the assessed scenarios.

Fact sheets, detailed in deliverable report D.1.4.3, will summarize and visually present the contributions of various RDF to sustainability. These materials will include explanations tailored to different target audiences, enhancing decision-making by illustrating the impacts of RDF across selected UN sustainability categories: social-cultural, economic, and environmental.

The assessment evaluates RDF performance across these three dimensions, and the results will be presented using visual tools such as profile line diagrams, bar charts, and Likert scales. These formats will enable stakeholders to quickly compare the sustainability performance of various RDF options, focusing on environmental impacts, economic benefits, and social implications. The primary goal is to empower stakeholders to make informed decisions by understanding the trade-offs involved in adopting RDF for fertiliser production. Key findings will highlight strengths such as reduced reliance on fossil fuels and enhanced local value chains, while also addressing challenges like scalability, resource availability, and economic feasibility in certain contexts. By providing clear, targeted visualizations and explanatory texts, the project aims to make the sustainability impacts of RDF more accessible to stakeholders in NWE. These resources will support more sustainable farming practices and resource management by enabling a deeper understanding of the environmental, economic, and social benefits of RDF.

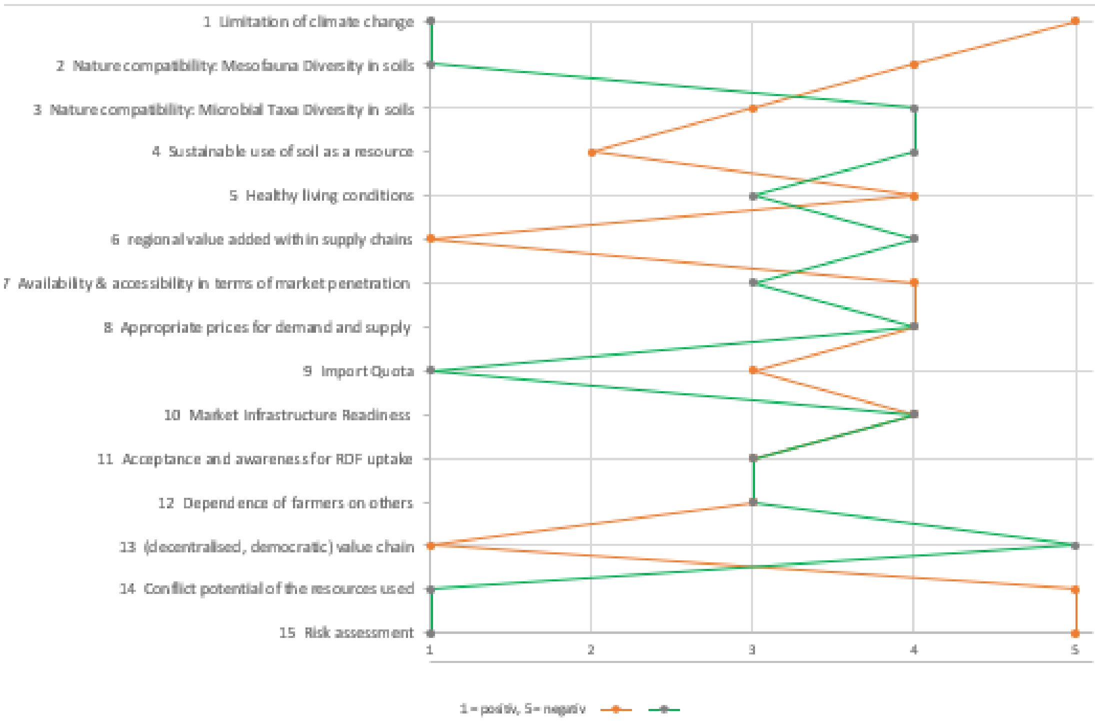


Figure 6: Visualisation of SA-4F Assessment (own figure)

# 5 Outlook for Future Research on Adaptation of the Multi-Criteria Sustainability Assessment for RDF

The multi-criteria sustainability assessment methodology developed for RDF offers significant potential for adaptation and application to specific regional contexts, such as federal states in Germany or other territorially defined areas in NWE. Regional characteristics, such as soil composition, crop types, climate conditions, and regulatory frameworks, play a critical role in determining the effectiveness and sustainability of RDF. Future research could explore these factors in depth, tailoring the assessment to account for specific local conditions and needs. Key areas for focused, general and region-specific research include:

- Blends of RDF

Future research could explore the potential and performance of RDF blends, combining various recycling-derived fertilisers to optimize nutrient profiles and adapt them to specific crop and soil requirements. This approach would aim to assess how blending different RDF could address nutrient imbalances, improve soil health, and support more resilient agricultural systems.

- Customization of Assessment Criteria for Local Relevance:

Future studies could adapt the 15 sustainability criteria to align more closely with regional priorities and SD goals. For example, areas facing high quantities of specific organic waste/ by-products availability or specific demands on specific fertilisers/blends could adapt the comparative scenarios with other RDF value chains.

- Territorial-Specific Environmental Impact:

Research could delve into localized ecological impacts of RDF use, considering factors like regional biodiversity, water sources, and soil health. Regions with fragile ecosystems or distinct natural resources might have different RDF requirements or restrictions, and the assessment could help identify sustainable RDF options that support local conservation goals.

- Economic and Social Implications of RDF Adoption in Regional Markets:

The economic viability of RDF may vary across regions, particularly in terms of costs, available infrastructure, and market demand. A region-specific adaptation of the assessment could evaluate how RDF use impacts local economies, job creation, and rural development, providing insights into the social acceptability and economic sustainability of RDF within specific regions.

- Policy and Regulatory Alignment:

Regional application of the assessment could incorporate local policies, regulations, and incentives that affect RDF production, distribution, and usage. This approach would offer policymakers a tailored tool for assessing RDF alignment with regional sustainability objectives and help in crafting region-specific guidelines to promote sustainable fertiliser practices.

By conducting in-depth, regionally focused studies, the sustainability assessment methodology for RDF can be refined and made more relevant to specific local contexts. This approach would provide valuable insights for stakeholders, enabling more precise and impactful decisions in the transition to sustainable agricultural practices tailored to regional needs.

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